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Army Engineer Waterways Experiment Station
Vicksburg, Mississippi

June 1975

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June 2-6, 1975

Detroit-Houghton, Michigan

Mobility and Environmental Systems Laboratory
U. S. Army Engineer Waterways Experiment Station
P. O. Box 631, Vicksburg, Miss. 39180

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The four papers herein were presented at the Fifth International Conference of the International Society for Terrain-Vehicle Systems held at Detroit and Houghton, Michigan on 2-6 June 1975 by personnel of the Mobility and Environmental System Laboratory, U. S. Army Engineer Waterways Experiment Station. The papers which were also published in the the Proceedings, Volume IV, U. S. Army Mobility Evaluation Methodology, describe the current status of the methodology for evaluating the effectiveness of ground vehicles. The first paper, The U. S. Army Mobility Model (AMM-75), describes the second (Continued)

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generation version of a comprehensive analytical model for evaluating the mobility of ground vehicle systems and the modifications that distinguish it from the first generation (AMC-71) version. The second paper, Terrain Modeling to Support Mobility Evaluation, describes the procedure and recent developments in terrain modeling to evaluate ground mobility. The third paper, Ride Dynamics Module for AMM-75 Ground Mobility Model, describes the computer module for simulating the ride and shock response of any rigid-framed vehicle and determining the relations necessary for input to the AMM-75 Ground Mobility Model to assess the effects of ride- and shock-limiting speeds on mobility. The fourth paper, Validation of the AMC-71 Mobility Model, describes the results of a comprehensive experimental program to validate and evaluate predictions of vehicle performance derived from the first generation (AMC-71) Mobility Model.

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PREFACE

The papers herein were presented at the 5th International Conference of the International Society for Terrain-Vehicle Systems held at Detroit-Houghton, Michigan, on 2-6 June 1975 by personnel of the Mobility and Environmental Laboratory (MESL), U. S. Army Engineer Waterways Experiment Station (WES), under the general supervision of Mr. W. G. Shockley, Chief, MESL. The papers were also published in Proceeaings, Volume IV, U. S. Army Mobility Evaluation Methodology.

The Director of WES during the publication of this report was COL G. H. Hilt, CE. Technical Director was Mr. F. R. Brown.

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CONVERSION FACTORS, U. S. CUSTOMARY TO METRIC (SI)
AND METRIC (SI) TO U. S. CUSTOMARY UNITS OF MEASUREMENT

Units of measurement used in this volume can be converted as follows:

Multiply	By	To Obtain
U. S. Customary to Metric (SI)		
inches	25.4	millimetres
square inches	0.000645	square metres
feet	0.3048	metres
feet per minute	0.00008467	metres per second
feet per second squared	0.3048	metres per second squared
miles (U. S. statute) per hour	1.6093	kilometres per hour
pounds (mass)	0.45359	kilograms
pounds (force)	4.4482	newtons
pounds (force) per inch	175.12	newtons per metre
pounds (force) per square inch	6894.757	pascal
pounds-inches	0.11298	newton-metres
pounds per second	0.45359	kilograms per second
kips (force)	4.4482	kilonewtons
degree (angle)	0.01745	radians
Metric (SI) to U. S. Customary		
metres	3.2808	feet
radians	57.2957	degrees (angular)

THE U. S. ARMY MOBILITY MODEL (AMM-75)

by

M. P. Jurkat, C. J. Nuttall, and P. W. Haley

Abstract

A primary goal of U. S. Army mobility research is the development of validated, objective methodology to support decision processes relative to the design, procurement, and deployment of military vehicles. As a step toward that end, a comprehensive analytical model for evaluating the mobility of ground vehicle systems has been implemented in a large-scale digital computer simulation. The model employs existing vehicle mechanics technology to predict individual facets of system performance and new analysis and programming techniques to account for their interaction.

In 1971, the then state-of-the-art was collected in a first version called AMC-71. This paper briefly describes the second generation of that model, AMM-75, and the modifications that distinguish the two versions.

Introduction

Rational design and selection of Army ground vehicles require objective evaluation of an ever-increasing number of vehicle and vehicle system options. Technology, threat, operational requirements, and cost constraints change with time. Current postures must be reexamined, new options evaluated, and new trade-offs and decisions made. In the single area of combat vehicles, for example, changes in one or another influencing factor might require trade-offs that run the gamut from opting for an air or ground system, through choosing wheels, tracks or air cushions, to designating a new tire.

The Mobility Systems Laboratory of the U. S. Army Tank-Automotive Command (TACOM), the U. S. Army Engineer Waterways Experiment Station (WES), and the U. S. Army Cold Regions Research and Engineering Laboratory are the government laboratories responsible for conducting ground mobility research for the U. S. Army Materiel Command (AMC). In 1971, a unified AMC ground mobility program was implemented that specifically geared the capabilities of all three laboratories to achieve common goals.

As a first step in the unified program, a detailed review was made of existing vehicle mobility technology and of the problems and requirements of the various engineering practitioners associated with the military vehicle life cycle. One basic requirement was identified as common to all practitioners surveyed: the need for an objective analytical procedure for quantitatively assessing the performance of a vehicle in a specified operational environment.

In theory, a single methodology can serve the needs of all major practitioners, provided it relates vehicle performance to basic characteristics of the vehicle-driver-terrain system at appropriate levels of detail.

Three principal categories of potential users of the methodology were identified: the vehicle development community, the vehicle procurement community, and the vehicle user community (Figure 1). The greatest level of detail is needed by the design and development engineer (vehicle design and development community) who is interested in subtle engineering details--for example, wheel geometry, sprung masses, spring rates, track widths, etc.--and their interactions with soil strength, tree stems of various sizes and spacings, approach angles in ditches and streams, etc. At the other end of the spectrum is the strategic planner (user community), who is interested in such highly aggregated characteristics as the average cross-country speed of a given vehicle throughout a specified region--the net result of many interactions of the engineering details with features of the total operational environment. To be responsive to the needs of all three user communities, the methodology must be flexible enough to provide compatible results at many levels and in an appropriate variety of formats.

Interest in a single, unified methodology applicable to the needs of these principal users led to the creation of a cross-country vehicle computer simulation combining the best available knowledge and models of the day. Much of this knowledge was collected in Reference 1. The first realization of the simulation was a series of computer programs known as the AMC-71 mobility model, called AMC-71 for short.[2] This model first became operational in 1971; it was published in 1973. It was conceived as the first generation of a family whose descendants, under the evolutionary pressures of subsequent research and validation testing results, application experiences, and growing user requirements, would be characterized by greater accuracy and applicability. A relatively current status report may be found in Reference 3, after which this presentation is patterned.

The first descendant, to be known as AMM-75, is in the final stages of preparation. Planned for release by the fall of 1975, its major features are highlighted in the description that follows.

Modeling Off-Road Vehicle Mobility

In undertaking mobility modeling, the first question to be answered was the seemingly easy one: What is mobility? The answer had been elusive for many years. Semantic reasons can be traced to the beginnings of mobility research, but there was also a pervasive reluctance to accept the simple fact that even intuitive notions about a vehicle's mobility depend greatly on the conditions under which it is operating. By the mid-1960s, however, a consensus had emerged that the maximum feasible speed-made-good* by a vehicle between two points in a given terrain was a suitable measure of its intrinsic mobility in that situation.

This definition not only identified the engineering measure of mobility, but also its dependence on both terrain and mission. When, at a suitably high resolution, the terrain involved presents the identical set of impediments to vehicle travel throughout its extent, mobility in

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* Speed-made-good between two points is the straight-line distance between them divided by total travel time, irrespective of path.

that terrain (ignoring edge effects) is the vehicle's maximum straight-line speed as limited only by those impediments. But when, as is typically the case, the terrain is not so homogeneous, the problem immediately becomes more complex. Maximum speed-made-good then becomes an interactive function of terrain variations, end points specified, and the path selected. (Note that the last two constitute at least part of a detailed mission statement.)

AMC Mobility Model Approach

The AMC mobility model deliberately represents real terrain as a mosaic of terrain units within each of which the terrain is considered sufficiently uniform to permit use of the simple, maximum straight-line speed of the vehicle to define its mobility in, along, or across that terrain unit.

Maximum speed predictions are made for each terrain unit without concern for whether or not distances within the unit are adequate to permit the vehicle to reach the predicted maximum.

This vehicle and terrain-specific speed prediction is the basic output of the model. The model, in addition, generates data that may be used to predict operational vibration levels, mission fuel consumption, etc., and provides diagnostic information as to the factors limiting speed performance in the terrain unit.

The speed and other performance predictions for all terrain units in an area can be incorporated into maps that specify feasible levels of performance that a given vehicle might achieve at all points in the area. At this point, the output is reasonably general and is essentially independent of mission and operational scenario influences.

The basic data constituting the maps must usually be further processed to meet the needs of specific users. These needs vary from relatively simple statistics or indices reflecting overall vehicle compatibility with the terrain, to extensive analyses involving detailed or generalized missions. At present only one output processer is considered a standard part of AMM-75. This post-processer accumulates a

speed for a single vehicle in a single areal terrain patch or terrain unit.

b. The linear feature module, which computes the minimum feasible time for a single vehicle, aided or unaided, to cross a uniform segment of a significant linear terrain feature such as a stream, ditch, or embankment.

c. The on-road module, which computes the maximum feasible speed of a single vehicle traveling along a uniform segment of a road or trail.

These three modules have been and are still able to be used separately or with output superimposed. A new feature of AMM-75 is the ability to simulate travel from terrain unit to terrain unit in the sequence given by the terrain input file. In this mode, known as the traverse mode, sufficient output data can be provided so that the user may calculate acceleration and deceleration times and distances between and across terrain unit boundaries, and thereby determine actual travel time and speed-made-good over a chosen route.

All three modules draw from a common data base that describes quantitatively the vehicle, the driver, and the terrain to be examined in the simulation. The general content of the data base is shown in Table 1.

Model Inputs and Preprocessers

Terrain

For the purposes of the model, each terrain unit is described at any given time by values for a series of 22 mathematically independent terrain factors for an areal unit (including lake and marsh factors), 10 for the cross section of a linear feature to be negotiated, and 9 to quantify a road segment (Tables 2 and 3). General-purpose terrain data also include separate values for several terrain factor values that vary during the year. For example, at present such general data for areal terrain include four values for soil strength (dry, average, wet, and wet-wet seasons) and four seasonal values for recognition distances in

statistical picture of maximum feasible speeds in the terrain, and of the terrain-driver-vehicle interactions that account for speed limits or NOGO situations. (AMC-71 includes a path selection model, which chooses the minimum time path from a network of possible paths, based on speeds along the network links predicted by the mobility model. While this model is not a standard part of AMM-75, it can be used with AMM-75 for special studies.)

Overall Structure of AMC Mobility Model

In formulating AMC-71, it was recognized that its ultimate usefulness to decision makers in the vehicle development, procurement, and user communities would depend upon its realism and credibility.[4] These perceived requirements led to several more concrete objectives related to the overall structure of the model. It was determined that the model should be designed to:

a. Allow validation by parts and as a whole.

b. Make a clear distinction between engineering predictions and any whose outcome depends significantly upon human judgment, with the latter kept visible and accessible to the model user.

c. Be updated readily in response to new vehicle and vehicle-terrain technology.

d. Use measured subsystem performance data in place of analytical predictions when and as available and desired.

These objectives, plus the primary goal of supporting vehicle decision making at the several levels, clearly dictated a highly modular structure that could both provide and accept data at the subsystem level, as well as make predictions for the vehicle as a whole. The resulting gross structure of the model is illustrated in Figure 2.

At the heart of the model are three independent computational modules, each comprised of analytical relations derived from laboratory and field research, suitably coupled in the particular type of operation:

a. The areal patch module, which computes the maximum feasible

vegetated areas. Similar variations in effective ground roughness, resulting from seasonal changes in soil moisture (including freezing) and in the cultivation of farm land, can be envisioned for the future. Further details on the terrain factors used are given in Reference 5.

As discussed earlier, the basic approach to representing a complex terrain is to subdivide it into areal patches, linear feature segments, or road segments, each of which can be considered to be uniform within its bounds. This concept is implemented by dividing the range of each individual terrain factor value into a number of class intervals, based upon considerations of vehicle response sensitivity and practical measurement and mapping resolution problems. A patch or a segment is then defined by the condition that the class interval designator for each factor involved--22 areal, or 10 linear, or 9 road--is the same throughout. A new patch or segment is defined whenever one or more factors fall into a new class interval.

The terrain data base contains, for each uniform patch or segment, a series of numbers specifying the value for each of its factors. A sample of such a listing for areal terrain, and of the terrain factor complex map to which it relates is shown in Figure 3.* As suggested by Table 2, the terrain data base is in fact different for the three types of terrain (areal, linear, and on-road).

Before being used in the three computational modules, the basic terrain data are passed through a terrain data preprocesser. This preprocesser does three things:

a. Converts as necessary all data from the units in which they are stored to inches, pounds, seconds, and radians, which are used throughout the subsequent performance calculations.

b. Selects prestored soil strengths and visibility distances according to run specifications, which are supplied as part of the scenario data (see below).

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* In the example, the area within any areal terrain patch is represented by an integral number of rectangular cells, 127x106 m. This representation allows results to be output on a normal computer printer in the form of 1:25,000 maps.

c. Calculates from the terrain measurements in the basic terrain data a small number of mathematically dependent terrain variables used in the computational modules.

Vehicle

The vehicle is specified in the vehicle data base in terms of its basic geometric, inertial, and mechanical characteristics. The complete vehicle characterization as used by the performance computation modules includes measures of dynamic response to ground roughness and obstacle impact, and the clearance and traction requirements of the vehicle while it is negotiating a parametric series of discrete obstacles.* The model structure permits use at these points of appropriate data derived either from experiments or from supporting stand-alone simulations used as preprocessers. One supporting two-dimensional ride and obstacle crossing dynamics module for obtaining requisite dynamics responses[6] and a second supporting module for computing obstacle crossing traction requirements and interferences[7] are available as elements of the AMM-75 model. Both derive some required information from the basic vehicle data base, and both, when used, constitute stand-alone vehicle data preprocessers.

There is also an integral vehicle data preprocesser which, like the terrain data preprocesser, has three functions:

a. To convert vehicle input data to uniform inches, pounds, seconds, and radians.

b. To calculate, from the input data, controlling soil performance parameters and other simpler dependent vehicle variables subsequently used by the computational modules, but usually not readily measured on a vehicle or available in its engineering specifications.

c. To compute the basic steady-state traction versus speed characteristics of the vehicle power train, from engine and power train characteristics.

As in the case of dynamics responses and obstacle capabilities, the last item, the steady-state tractive force-speed relation, may be input directly from proving ground data, when available and desired.

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* A simpler obstacle-crossing model was integral to the AMC-71 areal module.

Details of the vehicle input data required for operation of the areal, linear feature, on-road, and obstacle negotiation modules are given in Table 4. The two-dimensional ride and obstacle impact dynamics simulation requires special, detailed spring and damping data and mass properties not included in Table 4, but indicated in Reference 6.

Driver

The driver attributes used in the model characterize the driver in terms of his limiting tolerance to shock and vibration and his ability to perceive and react to visual stimuli affecting his behavior as a vehicle controller. While these attributes are identified in Figure 2 and Table 1 as part of the data base, in AMC-71 they are built into the program. AMM-75 provides for their specific identification and user control so that the effects of various levels of driver motivation, associated with combat or resupply missions, for example, can be considered.

Scenario

Several optional features are available to the user of AMM-75 (weather, presumed driver motivation, operational variations in tire inflation) which allow him to match the model predictions to features or assumptions of the full operational scenario for which he requires the predictions. Model instructions which select and control these options are referred to as scenario inputs.

The scenario options for AMC-71 are limited to the specification of season which, when seasonal differences in soil strength constitute a part of the terrain data, allows selection of the soil strength according to the variations in soil moisture with seasonal rainfall. AMM-75 expands the scenario options to include specifications of:

a. Weather, which affects soil slipperiness and driving visibility, (including dry snow over frozen ground and associated conditions).

b. Several levels of operational influences on driver tolerances to ride vibrations and shock, and on driver strategy in negotiating vegetation and using brakes.

c. Reasonable play of tire pressure variations to suit the mode of operation--on-road, cross-country, and in sand.

In addition, the model can now be used under a simple scenario command to make predictions in relation to a traverse (given directional terrain data specifically along the traverse) as well as to make omnidirectional predictions for an area.

Stand-Alone Simulation Modules

As indicated above, the model is implemented by a series of independent modules. The terrain and vehicle preprocessers, already described, form two of these. Two further major stand-alone simulation modules will now be briefed.

Dynamics module

The areal module examines as possible vehicle speed limits in a given terrain situation two limits which are functions of vehicle dynamic responses: speed as limited by the driver's tolerance to his vibrational environment when the vehicle is operating over continuously rough ground, and speed as limited by the driver's tolerance to impact received while the vehicle is crossing discrete obstacles. It is assumed that the driver will adjust his speed to ensure that his tolerance levels will not be exceeded.

The ride dynamics module of AMM-75[6] computes accelerations and motions at the driver's station (and other locations, if desired) while the vehicle is operating at any given speed over any given terrain profile. The profile may be continuously, randomly rough, may consist solely of a single discrete obstacle, or may be anything between. From the computed motions, associated with driver modeling and specified tolerance criteria, simple relations are developed for a given vehicle between relevant terrain measurements and maximum tolerable speed. The terrain measurement to which ride speed is related is the root mean square (rms) elevation of the ground profile (with terrain slopes and long-wavelength components removed). The terrain descriptors for obstacles are obstacle height and obstacle spacing.

The terrain parameters involved, rms elevation and obstacle height and spacing, are factors quantified in each patch description, and rms

elevation is specified for each road segment. Preprocessing of the vehicle data in the ride dynamics module provides an expedient means of predicting dynamics-based speed in the patch and road segment modules via a simple, rapid table-lookup process.

The currently implemented ride dyanmics module is a digital simulation that treats vehicle motions in the center-line plane only (two dimensions). It is a generalized model that will handle any rigid-frame vehicle on tracks and/or tires, with any suspension. Tires are modeled using a segmented wheel representation,[8] and a variation of this representation is used to introduce first-order coupling of the road wheels on a tracked vehicle by its tracks. The simulation requires detailed vehicle data that are not used in the speed prediction modules and not shown in Table 4. The complete listing of vehicle input data used is given in Reference 6.

Driver model and tolerance criteria. It has been shown empirically that, in the continuous roughness situation, driver tolerance is a function of the vibrational power being absorbed by the body.[9] The same work showed that the tolerance limit for representative young American males is approximately 6 watts of continuously absorbed power, and the research resulted in a relatively simple model for power absorption by the body. The body power absorption model, based upon shaping filters applied to the decomposed acceleration spectrum at the driver's station, is an integral part of the AMM-75 two-dimensional dynamics simulation.

In AMC-71, only the 6 watt criterion was used to determine a given vehicle's speed as limited by rms roughness. More recent measurements in the field have shown that with sufficient motivation young military drivers will tolerate up to 15 watts for periods of many minutes. Accordingly, AMM-75 will accept as vehicle data a series of ride speed versus rms elevation relations, each corresponding to a different absorbed power level, and will use these to select ride-speed limits according to the operationally related level called for by the scenario. The ride dynamics module will, of course, produce the required additional data, but some increased running time is involved.

The criterion limiting the speed of a vehicle crossing a single discrete obstacle, or a series of closely, regularly spaced obstacles, is a peak acceleration at the driver's seat of 2.5 g passing a 30-Hz filter. Data relating the 2.5-g speed limit to obstacle height and spacing can be developed in the ride dynamics module by inputting appropriate profiles.

AMM-75 requires two obstacle impact relations: the first, speed versus obstacle height for a single obstacle (spacing very great); and the second, speed versus regular obstacle spacing for that single obstacle height (from the single obstacle relation) which limits vehicle speed to a maximum of 15 mph (24 kpm). For obstacles spaced at greater than two vehicle lengths, the single-obstacle speed versus obstacle height relation is used. For closer spacings, the least speed allowable by either relation is selected.

Obstacle-crossing module

A new module is provided in AMM-75 to determine interferences and traction requirements when vehicles are crossing the kind of minor ditches and mounds characterized as part of the areal terrain.[7] It is used as a stand-alone preprocessor module to the areal module of AMM-75.

The new obstacle-crossing module simulates the inclination and position, interferences, and traction requirements of a two-dimensional (center-line plane) vehicle crossing a single obstacle of any profile configuration or any arbitrary sequence of such obstacles. The module determines a series of static equilibrium positions of the vehicle as it progresses across the obstacle profile. Extent of interference is determined by comparison of the obstacle profile and the displaced vehicle bottom profile. Traction demand at each position is determined by the forces on driven running gear elements, tangential to the obstacle surface, required to maintain the vehicle's static position. Pitch compliance of suspension elements and of frame articulation (as at pitch joints, trailer hitches, etc) is accounted for.

In AMC-71, the determination of vehicle obstacle negotiation in an areal terrain unit was performed repeatedly within the areal module for

each terrain unit as it occurred. This proved time-consuming and was unnecessary for two terrain units with the same obstacles. The AMC-71 obstacle routine made simplified tests for interference and traction requirements at a limited number of critical stages in the process of obstacle negotiation (for instance, front-end interference approach angle at initial obstacle contact, belly interference across the top of a mound, and traction required on the upslope side.) The routine assumed a rigid frame vehicle and a 2-axle or rigid track running gear with no suspension compliance. The AMC-71 modeling approach requires that the designer of the routine foresee all possible cases of interference for all types of vehicles. When this critical check technique is to be applied to suspended multi-axle vehicles, or to pitch-articulated vehicles, the number of tests to be made becomes very large and too much reliance is placed on the model designer's intuition. The chance of mistakes is great.

In response to these objections and with the desire to allow AMM-75 to treat properly a greater variety of more realistic vehicle designs, including articulated vehicles, softly-sprung vehicles, and vehicles with large variations in weight distribution from one running gear unit to another, the more detailed equilibrium calculation approach was adopted for interference and traction. In this technique, the vehicle, mathematically, is moved across the obstacle in fixed steps. At each step the vehicle's equilibrium elevation and attitude are calculated by minimizing the potential energy of height and suspension. Currently, the module is operational for wheeled vehicles on obstacles for which relatively small pitch angles can be assumed. This allows each equilibrium position to be found by the solution of linear equations.

In order to assure that all possible locations where interference can occur are at least approximated, the step size across the obstacle must be small compared to the size of the obstacle and vehicle. This forces the new model to consume considerable time to check each obstacle-vehicle combination. To minimize total computing time, the obstacle module is run out of the main stream of the AMM-75 processing modules. This is feasible because in AMM-75, as in AMC-71, obstacle cross sections

characterized as part of the areal terrain (as distinct from major obstacles which are treated separately as linear features) are considered symmetrical and are defined by only three parameters: height (or depth), approach angle, and width.

The new model, run as a preprocesser module, produces a table of minimum clearances (or maximum interferences) and average and maximum force required to cross a representative sample of obstacles defined by combinations of obstacle dimensions varied over the ranges appropriate for features included in the areal terrain description. This is done only once for each vehicle. Included in the AMM-75 areal module is a three-dimensional linear interpolation routine which, for any given set of obstacle parameters, approximates from the derived table the corresponding vehicle clearance (or interference) and associated traction requirements. Obviously, the more entries there are in the table, the more precise will be the determination.

Main Computational Modules

The highly iterative computations required to predict vehicle performance in each of the many terrain units needed to describe even limited geographic areas are carried out in the three main computational modules. Each of these involve only direct arithmetic algorithms which are rapidly processed in modern computers. In AMM-75, even the integrations required to compute acceleration and deceleration between obstacles within an areal patch are expressed in closed, algebraic form.

Terrain input data include a flag, which signifies to the model whether the data describe an areal patch, a linear feature segment, or a road segment. This flag calls up the appropriate computational module.

Areal terrain unit module

This module calculates the maximum speed a vehicle could achieve and maintain while crossing an areal terrain unit. The speed is limited by one or a combination of the following factors:

a. Traction available to overcome the combined resistances of soil, slope, obstacles, and vegetation.

b. Driver discomfort in negotiating rough terrain (ride comfort) and his tolerance to vegetation* and obstacle impacts.

c. Driver reluctance to proceed faster than the speed at which the vehicle could decelerate to a stop within the, possibly limited, visibility distance prevailing in the areal unit (braking-visility limit).

d. Maneuvering to avoid trees and/or obstacles.

e. Acceleration and deceleration between obstacles if they are to be overridden.

Figure 4 shows a general flow chart of how the calculations of the areal module in AMM-75 are organized.

After determination of some vehicle and terrain-dependent factors used repetitively in the patch computation (1),** the module is entered with the relation between vehicle steady-state speed and theoretical tractive force and with the minimum soil strength that the vehicle requires to maintain headway on level, weak soils. These data are provided by the vehicle data preprocesser. Soil and slope resistances (2) and braking force limits (4) are computed, and the basic tractive force-speed relation is modified to account for soil-limited traction, soil and slope resistances, and resulting tire or track slip. Forces required to override prevailing tree stems are calculated for eight cases (3): first, overriding only the smallest stems, then overriding the next largest class of stems as well, etc., until in the eighth case all stems are being overridden.

Stem override resistances are combined with the modified tractive force-speed relation to predict nine speeds as limited by basic resistances (5). (The ninth speed corresponds to avoiding all tree stems.)

Maximum braking force and recognition distance are combined to compute a visibility-limited speed (6). Resistance and visibility-limited speeds are compared to the speed limited by tire loading (7), if

* Checked as part of the areal terrain unit module.

** Numbers in parenthesis correspond to numbers in Figure 4.

applicable, and to the speed limit imposed by driver tolerance to vehicle motions resulting from ground roughness (8). The least of these for each tree override-and-avoid option becomes the maximum speed possible between obstacles by that option, except for degradation due to maneuvering (9).

Obstacle avoidance and/or the tree avoidance implied by limited stem override requires the vehicle to maneuver (or may be impossible). Using speed reduction factors (derived in 1) associated with avoiding all obstacles (if possible) <u>and</u> avoiding the appropriate classes of tree stems, a series of nine possible speeds (including zero, or NOGO) is computed (10).

A similar set of nine speed predictions is made for the vehicle maneuvering to avoid tree stems only (10). These are further modified by several obstacle crossing considerations.

Possible NOGO interference between the vehicle and the obstacle is checked (12). If obstacle crossing proves to be NOGO, all associated vegetation override and avoid options are also NOGO. If there are no critical interferences, the increase in traction required to negotiate the obstacle is determined (12).

Next, obstacle approach speed and the speed at which the vehicle will depart the obstacle, as a result of the momentarily added resistance encountered, are computed (13). Obstacle approach speed is taken as the lesser of the speed between obstacles, reduced for maneuver required by each stem override and avoid option, and the speed limited by the driver to control his crossing impact (11). Speeds off the obstacle are computed on the basis solely of the soil- and slope-modified tractive force-speed relation (22), i.e. before the tractive force speed relation is modified to account for vegetation override forces, the traction increment required for obstacle negotiation, or any kinetic energy available as a result of the associated obstacle approach speed (13).

Final average speed in the patch for each of the nine tree stem override and avoid options, while the vehicle is overriding patch obstacles, is computed from the speed profile resulting, in general, from

considering the vehicle to accelerate from the assigned speed off the obstacle to the allowable speed between obstacles (or to a lesser speed if obstacle spacing is insufficient), to brake to the allowable obstacle approach speed, and to cross the obstacle per se at the computed crossing speed.

Following a final check to ensure that traction and kinetic energy are sufficient for single-tree overrides called for (and possible resetting of speeds for some options to NOGO) a single maximum in-patch speed (for the direction of travel being considered relative to the in-unit slope) is selected from among the nine available values associated with obstacle avoidance and the nine for the obstacle-override cases. If all 18 options are NOGO, the patch is NOGO for the direction of travel. If several speeds are given, selection is made by one of two logics according to scenario input instructions.

In AMC-71 the driver was assumed to be both omniscient and somewhat mad. Accordingly, the maximum speed possible by any of the 18 strategies was selected as the final speed prediction for the terrain unit (and slope direction). Field tests have shown, however, that a real driver does not often behave in this ideal manner when driving among trees. Rather, he will take heroic measures to reach some reasonable minimum speed, but will not continue such efforts when those measures involve knocking down trees that he judges it imprudent to attack, even though by doing so he could go still faster. In AMM-75, either assignment of maximum speed may be made: the absolute maximum which addresses the vehicle's ultimate potential, or a lesser value which in effect models actual driver behavior more closely.

In AMM-75, if the scenario data specify a traverse prediction, the in-unit speed and other predictions are complete at this point, and the model stores those results specified by the user and goes on to consider the next terrain unit (or next vehicle, condition, etc). When a full areal prediction is called for, the entire computation is repeated three times: once for the vehicle operating up the in-unit slope, once across the slope, and once down the slope. Desired data are stored from each such run prior to the next, and at the conclusion of the third run, the

three speeds are averaged. Averaging is done on the assumption that one-third of the distance* will be traveled in each direction, resulting in an omnidirectional mean.

The areal module of AMM-75, as compared with that of AMC-71, is significantly improved in several other respects.

a. AMC-71 assumes all running gears of a vehicle to be powered, geometrically identical, and equally loaded. AMM-75 can simulate vehicles and vehicle combinations having various configurations of powered, braked, and towed wheels and tracks, variously loaded. This is done by calculating the tractive effort and motion resistance of the vehicle running gear one element at a time and summing for the whole configuration. A separate value of excess vehicle cone index (VCI) is calculated for each running gear and then relations presented in References 1 and 10 are used to find traction and resistance coefficients for that running gear. The load (possibly modified for slope or buoyancy as specified by the terrain unit) and the running gear VCI's are then used to calculate overall maximum tractive effort and resistance. This allows the modeling of vehicles such as half-tracks; towed, powered, or braked trailers; articulated vehicles; and vehicles with gross variations in load distributions and running-gear geometry.

b. AMM-75 contains equations that allow simulations of travel across slippery soils, muskeg, and shallow dry snow in addition to the fine- and coarse-grained soils covered in AMC-71. Slipperiness effects are included whenever the scenario calls for rain or standing water and soil surfaces are flooded or locally very wet. Separate relations are used for fat clay soils, which are impervious to water, and for other more

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* $V_{av} = \dfrac{3}{\dfrac{1}{V_{up}} + \dfrac{1}{V_{across}} + \dfrac{1}{V_{down}}}$, i.e. mathematically the harmonic average of the three speeds.

pervious fine-grained soils. Where soil is relatively soft, slipperiness is not a factor. When the surface is very hard, the slipperiness factor becomes constant, indicating a "skating" condition. Muskeg performance relations included are those published in Reference 11. Shallow snow is defined as snow covering frozen ground at a depth less than the characteristic length of the tire or less than one third of the characteristic length of the track. To calculate the drawbar-pull and resistance coefficients for shallow snow, the model uses snow effective cohesion, internal friction, and specific weight. Traction is calculated by means of the familiar Coulomb relation, and motion resistance is obtained by means of two empirical functions (based upon limited tests in shallow dry snow over the years 1955 through 1972), one for tracked vehicles, one for wheeled. In both relations the fundamental prediction term involves the ratio of nominal running gear contact length to snow depth after compression of the snow to a specific gravity of 0.4. Drawbar-pull or net traction available is taken as the excess of traction over motion resistance.

c. The net tractive performance of wheeled vehicles in soils and dry snow is significantly influenced by tire inflation pressure, load and resulting tire deflection, and to a lesser extent by the fitting of slip-limiting or locking differentials. The effects of these factors are modeled in the revised soil submodel in AMM-75. A new speed limit is also introduced to ensure that the speed reduction which must accompany operations at reduced tire inflations is accounted for. Separate inflation versus speed-limit relations are used for bias-ply and radial tire construction.

d. In AMC-71 resistance encountered during obstacle crossing in an area is averaged over the entire patch area. In AMM-75, the full value of this resistance is introduced at the obstacles only, giving rise to possible deceleration and

acceleration at obstacles in the same general manner as does the driver's slowing to reduce obstacle crossing impact to the tolerable level.

e. The relation between vehicle speed and tractive effort available at that speed is used throughout the module. In AMC-71 this relation is kept as a table, which necessitates frequent searches and interpolations. In AMM-75 the tractive force-speed is modeled as a series of quadratic equations, one for each gear or section of a gear range. The vehicle preprocesser initially fits the quadratics to the theoretical rimpull power train curve. The areal module then modifies the quadratics for traction limit, for slope, and for running-gear longitudinal slip. The availability of the tractive effort in quadratic form allows closed-form integration in the calculation of acceleration times and distances. This provides for a more precise and rapid calculation of average speed as a result of acceleration and deceleration between obstacles than was available in AMC-71.

f. The effects of rotating masses (gears, wheels, tracks, etc.), which must be rotationally accelerated as the vehicle pass per se is accelerated linearly, have been incorporated in AMM-75 computations of vehicle acceleration and deceleration performance. This is done by using values for the equivalent mass factor (apparent mass/actual mass) for the vehicle in each gear, in the vehicle power train data.

g. In AMM-75 final obstacle and vegetation-override GO/NOGO checks are made at the end of the speed computations for a terrain unit where the best estimate of approach speeds is available. This permits more rational assessment of kinetic energy availability to overcome any traction deficits. In AMC-71 these checks are made with basic soil- and slope-limited speeds, which are often reduced later in the computations by further speed-limiting considerations.

Linear feature crossing module

In context of AMC-71 and AMM-75, a linear feature is a distinct terrain element such as a stream, man-made drainge ditch, canal, escarpment, or a highway or railroad embankment, which is a potential barrier to vehicle movement normal to its characteristic length. By and large, most such features are represented by lines on a good 1:50,000 topographic map of an area.

Vehicle performance in crossing linear features requires somewhat different modeling from that used to deal with areal terrain because a vehicle does not necessarily negotiate a linear feature in the same manner that it does areal terrain. While crossing of smaller features is similar to the crossing of obstacles characterized as features of an areal patch, the linear feature obstacles themselves will generally be more severe. A model of the physical encounter must be able to deal properly with large changes in vehicle attitude, with load changes arising from this and from buoyancy effects, with complex obstacle cross sections, and complex changes in soil composition and strength across the section.

All of the above considerations apply also to modeling the crossing of larger linear features, plus the additional fact that complete crossing of a large feature need not be done on a single cross section. Successful negotiation often requires that the vehicle enter the feature at one point along its length, and remain "in" it (if it is a stream) or "on" it (if it is a road embankment) for some distance until a suitable exit point is found. Because linear features are frequently severe barriers, realistic predictions of crossing times must therefore include an assessment of alternatives to headlong crossing at a given site. These alternatives should include possible search distances to find suitable exit sites, and even to find a bridge or other gap in the barrier.

The linear feature crossing module[12] of AMM-75 is structured to address all of these special problems, albeit some on as yet relatively simple bases. The general flow of computations is shown in Figure 5.

The basic output of the module is a GO or NOGO determination for

a given vehicle crossing a linear feature at a single, fully specified cross section characteristic of cross sections throughout some length of the feature. Such a nominally uniform length of the feature is called a linear feature segment, or a linear terrain unit. If the vehicle can cross, crossing time from bank top to bank top is computed. If the situation is NOGO, reasons are shown and an index of relative crossing difficulty is computed which can be used in a suitable output processer to assess delay times or to call for use of alternative crossing sites according to the user's full scenario. When area-wide predictions are required by the user (specified at run time), crossing is checked in both directions. For a traverse, crossing is checked only in the direction required.

Regardless of whether the cross section is GO or NOGO, data to permit consideration of alternative crossing sites are also developed for each linear feature segment. By consulting statistics for the area (the natural river meanders which depend on gross topography, and bridge spacings) and/or speed predictions for the area made by the areal terrain modules, two mean distances and associated travel times in the areal terrain (along the feature, but not "in" or "on" it) are assigned. One distance-time is given to the nearest suitable bridge (if applicable), and the other distance-time is to the nearest crossable section. Where crossing NOGO is the result of exiting traction and/or vehicle-bank interference problems, the nearest crossable section is characterized by an exit "window".

For a linear terrain unit wide enough and otherwise suitable for vehicle travel along its length, a second mean distance and travel time to the nearest exit window are also determined, based upon predicted vehicle speed "on" or "in" the linear segment.

The outputs, GO/NOGO, reasons for NOGO, index of crossing difficulty and times to cross or to find other crossing sites, are returned to the user with no further analysis. How they are used to calculate traverse times or average speeds depends on the total operational scenario of the user. The model does not postulate a complete scenario.

Basic two-way GO/NOGO determinations may be coded simply and overlaid on an areal terrain speed map to provide a more complete picture of the cross-country movement problem presented to a vehicle by a given geographic locale under given weather conditions. The complete output data are suitable for statistical aggregation to show the compatibility of a vehicle with the terrain and conditions, or for the support of vehicle mobility evaluations based upon various mission profiles and presumed levels of support.

Road module

The road module calculates the maximum speed a vehicle can be expected to attain along a nominally uniform stretch of road, termed a road unit. Travel on super highways, primary and secondary roads, and trails is distinguished by specifying a road type and a surface condition factor. From these, values of tractive and rolling resistance coefficients for wheeled and tracked vehicles on surfaced roads are determined by a table look-up. For trails, surface condition is specified in terms of cone index (CI) or rating cone index (RCI). Traction, motion resistance, and slip are computed using the soil submodel of the areal module, with scenario weather factors used in the same way as in making off-road predictions.

Relations for computing vehicle performance on smooth, hard pavements are taken from the literature.[13, 14]

The structure of the road module, while much simpler, parallels that of the areal module. Separate speeds are computed as limited by available traction and countervailing resistances (rolling, aerodynamic, grade, and curvature), by ride dynamics (absorbed power), by visibility and braking, by tire load, inflation and construction, and by road curvature per se (a feature not directly considered in the areal module). The least of these five speeds is assigned as the maximum for the road unit (for the assumed direction relative to the specified grade).

The basic curvature speed limits are derived from AASHO experience data for the four classes of roads[15] under dry conditions and are not vehicle dependent. These are appropriately reduced for reduced traction conditions, and vehicle dependent checks are made for tipping or sliding while the vehicle is in the curve.

At the end of a computation, data required by the user are stored. If the model is run in the traverse mode, the model returns to compute values for the next unit; if in the areal mode, it automatically computes performance for both the up-grade and down-grade situations and at the conclusion computes the bidirectional (harmonic) average speed.

Scenario options are similar to those for the areal module.

Output processing

At the conclusion of each computation of vehicle speed in a single areal terrain or road unit, or time to cross a linear segment, a list of up to 600 computed values is deliberately kept temporarily available in the derived data base. Included are all intermediate computed speeds and forces, descriptors of the power train curve as modified by soil strength and resulting slip, and numerous flags indicating special circumstances. Those values (and only those values) desired by the user for further processing, specified by him prior to a run, are stored in a user-designated file before a new terrain unit is considered.

Data saved for further output processing may range from single, final speed predictions, through information needed to diagnose vehicle-terrain compatibility, to figures needed for fuel consumption calculations or to introduce into traverse speed predictions the effects of acceleration and deceleration across terrain unit boundaries.

The basic in-unit speed predictions for a vehicle are the most fundamental output of the model. When these predictions are made for all areal terrain units in a given geographic area, they may be aggregated to calculate various average speeds in the terrain by weighting in-unit speeds according to the relative areal occupancy of associated terrain units or to the relative operational importance of the areas, for example.

The most straightforward and general portrayal of the basic speed results is a mobility map (Figure 6), which indicates the speeds of which the vehicle is capable (including zero, the NOGO condition) throughout the area under consideration. The sample map displays

speeds in areal terrain patches only. Linear feature GO/NOGO characteristics can be superimposed to show where these constitute barriers, and a reasonably coded on-road speed map can also be overlaid. The mobility map is a suitable format for presentation of mobility data for many purposes--for example, as input to war gaming or other effectiveness analysis, or for operational planning. It is not directly suitable for applications of a parametric nature, such as assigning quantitative ratings to vehicle candidates for a given mission.

The development of a definitive parametric description of a vehicle's mobility is a task that has challenged vehicle researchers for many years. To date, no generally accepted definition has been forthcoming. However, substantial progess of a conceptual nature has been made during the past few years. The development of the AMM mobility model, which provides a mechanism to integrate the effects of diverse mobility impediments in accordance with their occurrence in the mission environment, constitutes a substantial contribution to this progress.

Because of the absence of a generally accepted parametric mobility description and the widely varying requirements and viewpoints of prospective model users, only one general-purpose output processer is considered to be a standard part of AMM-75. This routine provides a number of useful statistical interpretations of basic model output data for an area. Its principal product is a mobility profile (see Figure 7), which conveys a complete statistical description of a vehicle's mobility performance in all aspects save spatial distribution. The profile indicates the average speed the vehicle can sustain, as a function of the percent of the total area under consideration which it is able to avoid, assuming it avoids those areas posing the greatest impediment to its motion. For example, the intercept V_{90} = 13.5 mph at point A in Figure 7 denotes that the subject vehicle can average 13.5 mph (21.8 km/hr) in the area considered provided it can avoid the most difficult 10 percent of the terrain.

In addition to the mobility profile, the mobility statistics analysis also provides a set of diagnostic outputs to identify the specific mobility impediments limiting vehicle performance in each

terrain unit. These diagnostic outputs in their simplest form can be usefully portrayed in histogram form, as in Figure 8, to provide a vivid depiction of the relative significance of the various primary impediments for the particular terrain-vehicle combination considered. The results presented in Figure 8, for example, indicate that maneuvering among obstacles (factor 8) and crossing obstacles (factor 10) are the dominant performance-limiting factors in the situation illustrated. From a design viewpoint, this finding suggests that improving the vehicle's suspension to reduce accelerations during obstacles crossing and increasing its power and hence its acceleration capability would produce an improvement in overall performance. On the other hand, had factors 6 and 9 been the dominant speed limiters, increased vehicle power only would have been suggested.

Although the interface has not been specifically developed, AMM-75 will also readily support the best-route selection model that is a part of AMC-71, should this be required. The route selection model determines the route a vehicle would take to minimize travel time across a terrain area between two given points.

To determine the route, the terrain area is overlaid with a rectangular grid, and the vehicle is constrained to travel only along straight lines between grid coordinates. Travel times along the allowable paths are predicted by AMC-71 (or AMM-75). The particular combination of such line segments over which the vehicle can negotiate the area in the shortest time is determined by dynamic programming techniques.[16-18] No claim is made that this mathematically defined least-time route is related deterministically to the route that a particular driver would select under operational conditions. It is hypothesized, however, that speed values thus computed for a specific vehicle between a number of random point pairs within an area represent a meaningful quantitative measure of the vehicle's mobility in the terrain under consideration.

Other special-purpose output processers are already operational: to compute traverse speed (including acceleration and deceleration across terrain unit boundries), to compute fuel consumption, and to

produce speed maps on a high-speed computer printer, for example. In each case, the basic data developed in AMM-75 are essential, and the implementation relatively straightforward as computer programs go.

AMM-75, per se, is considered actually to end with basic performance predictions. These have been the crucial problem. Application routines, while interesting and often challenging, are best left to the user to tailor to his exact requirements of the moment.

Applications of Mobility Model

Intelligent application of the AMM-75 mobility model can contribute to every phase of the vehicle development process. The model can be particularly useful for:

a. Establishing mobility criteria to ensure a desired level of performance in a specified geographic area.

b. Determining and comparing the expected performance of various vehicle concepts in specified terrains.

c. Studying the effect of specific design changes on cross-country performance.

During the past two years to date, AMC-71 has been used with appropriate output analyses to develop terrain-specific mobility evaluations of a broad range of military vehicles in five principal geographic locales: two in temperate climates, two in dry desert areas, and one in a subtropical area largely in rice agriculture. These evaluations have affected decisions concerning the entire Army wheeled vehicle fleet and its high-mobility tactical truck components, the design of new main battle tanks, and the direction of self-propelled artillery and future Army scout vehicle developments.

These practical applications and the attendant opportunities to meet the vehicle user and his problems in real life and in real time, have been found useful in accelerating model development and validation. The most recently completed application, to the examination of high-mobility vehicles within actual full operational scenarios, for example, involved appropriately characterizing terrain in large new areas

and major extensions in model ouput processing. Under these pressures, rapid, new computerized digital terrain mapping methods were implemented,[5] along with compatible output routines that make combined on- and off-road traverse performance predictions directly from relatively simple map inputs.

Model Running Time

The AMC-71 mobility model is currently operational at WES, TACOM, and Stevens Institute of Technology. AMM-75 is being implemented now. AMC-71 has also been made available to a number of other users. AMC-71 can be run on both time-sharing and batch-processing computer systems. Representative current computer running times to make predictions for a single vehicle in 1000 areal patches, once terrain and vehicle data are made available, are:

Areal predictions	2 min
Statistical consolidation	3 min

Figures for AMM-75 are expected to be of the same order.

The present supporting two-dimensional ride dynamics simulation, used in batch mode to simulate a normal military vehicle, runs at 10-20 times real time on a large third-generation digital computer. For a single vehicle, approximately four runs (at different speeds) over each of four 300-ft stretches of randomly rough terrain having rms elevation values from 0.5 to 3-in. are required to define the ride-speed curves used in AMC-71 and AMC-75. A like amount of computation is required to develop the obstacle crossing speed-limit relations as functions of obstacle height and spacing used in AMC-75.

The new AMM-75 obstacle negotiation model, as presently implemented (without refinements to minimize running time), requires 3 min to cross a single obstacle. Full exercise of the computer programmer's art will cut this in half, but even then the computer time to develop a 4 height x 4 width x 4 angle matirx will be of the order of 100 min. AMM-75 is deliberately structured so that this model need be run only once for a given vehicle, regardless of the number of areas the vehicle is subsequently checked against.

Further Developments

With the implementation and release of AMM-75, one major objective of the mobility elevation methodology development program will be substantially completed. Nonetheless, considerable directly related work will remain:

- a. To validate the final AMM-75 algorithms and logic (the field validation program to date has dealt with AMC-71[19]) and make any necessary final adjustments.
- b. To further upgrade the vehicle ride dynamics, obstacle negotiation, and linear feature crossing simulations.
- c. To develop means to assess operationally reasonable time delays for NOGO situations.
- d. To introduce variability of driver skill as a function of training.
- e. To incorporate the model into the detailed vehicle design cycle through adapting it for use as an interactive computer-aided design and engineering tool.
- f. To assist model users in their applications of AMM-75.
- g. To manage the model once it is released; i.e. keep the full AMM-75 user community informed of all changes, from whatever quarter and of whatever magnitude, so that one, or two, or five years from now, all users will all have the same version at any given time.

With the successful demonstration by AMC-71 and AMM-75 of the potential benefits of deterministic engineering modeling of complex, terrain-dependent systems, emphasis is already rapidly shifting to new areas. Paramount among these are:

- a. The development of vehicle-terrain-driver specific engineering modeling of combat vehicle agility performance.
- b. The establishment of firm, supportive data interfaces between AMM-75 and higher order combat and logistics simulations.
- c. The development of terrain and mission specific reliability modeling and its integration into the overall mobility evaluation methodology.

d. The application of the modeling approach and philosophy demonstrated in AMM-75 to other important military and commercial activities whose effectiveness is highly terrain dependent, such as combat engineering operations in support of mobility, pipeline construction and surface mining.

Concluding Remarks

AMM-75 is considered to be the cornerstone of a new unified engineering methodology for answering a broad range of mobility-related questions. AMM-75 is incomplete in some respects, imperfect in most. That is the nature of any simulation, a fact of which modern decision makers are aware. Nonetheless, used and interpreted with an appreciation of its inherent limitations, AMM-75 provides the vehicle development, procurement, and user communities with a set of analytical tools for obtaining quantitative engineering information to satisfy their needs in a systematic manner.

AMC-71 and AMM-75 have also proven to be the communication link long needed between users and researchers to guide further research and to establish common ground for the solution of vehicle designer and user problems. They are providing, across time and across organizations, objective, consistent communication among all elements responsible for improved Army mobility. Decisions growing in large part from the resulting new levels of technical understanding and communication will determine the major characteristics of the Army's vehicle fleet into the 1980's and beyond.

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Table 1

Terrain, Vehicle, Driver Attributes Characterized in AMM-75 Mobility Model Data Base

Terrain	Vehicle	Driver
Surface composition	Geometric Characteristics	Reaction times
Type		Recognition distance
Strength	Inertial Characteristics	Acceleration and impact tolerances
Surface Geometry		
Slope/Altitude	Mechanical Characteristics	Minimum acceptable speeds
Discrete Obstacles		
Roughness		
Road Curvature/width/ Superelevation		
Vegetation		
Stem size & spacing		
Visibility		
Linear geometry		
Stream cross section		
Water velocity & depth		

TABLE 2

BASIC CONTENT OF TERRAIN DATA BANK FOR EACH TYPE OF PATCH OR SEGMENT

Terrain or Road Factor		Terrain Factor Family	Factor Complex
Off Road			
Slope		Surface Geometry	Areal (Patch)
Obstacle			
Approach angle	Obstacle Geometry	Surface Geometry	Areal (Patch)
Vertical magnitude	Obstacle Geometry	Surface Geometry	Areal (Patch)
Length	Obstacle Geometry	Surface Geometry	Areal (Patch)
Width	Obstacle Geometry	Surface Geometry	Areal (Patch)
Spacing	Obstacle Geometry	Surface Geometry	Areal (Patch)
Spacing type	Obstacle Geometry	Surface Geometry	Areal (Patch)
Surface Roughness*		Surface Geometry	Areal (Patch)
Vegetation			
Stem diameter	Vegetation Structure	Vegetation	Areal (Patch)
Stem spacing	Vegetation Structure	Vegetation	Areal (Patch)
Visibility*		Vegetation	Areal (Patch)
Surface Material			
Type		Surface Composition	Areal (Patch); Linear (Segment)
Mass strength*		Surface Composition	Areal (Patch); Linear (Segment)
Water cover			
Depth*		Surface Composition	Areal (Patch); Linear (Segment)
Current*		Surface Composition	Areal (Patch); Linear (Segment)
Width*		Surface Composition	Areal (Patch); Linear (Segment)
Left Approach Angle*		Surface Linear Geometry	Linear (Segment)
Right Approach Angle*		Surface Linear Geometry	Linear (Segment)
Differential Bank Height or differential vertical magnitude		Surface Linear Geometry	Linear (Segment)
Top width		Surface Linear Geometry	Linear (Segment)
Low bank height or least vertical magnitude		Surface Linear Geometry	Linear (Segment)
On Road			
Surface Material			
Type		Surface Composition	Road (Segment)
Surface Strength and traction properties*		Surface Composition	Road (Segment)
Slope		Surface Geometry	Road (Segment)
Elevation		Surface Geometry	Road (Segment)
Surface Roughness*		Surface Geometry	Road (Segment)
Curvature		Surface Geometry	Road (Segment)
Super-elevation		Surface Geometry	Road (Segment)
Visibility*		Surface Geometry	Road (Segment)
Width		Surface Geometry	Road (Segment)

* Complete data for an area may include several values for any or all of these quantities representing seasonal variations. At run time appropriate value(s) are selected by the run specification.

Table 3

Terrain Data Required for AMC Mobility Model

Terrain or Road Factor	Range
Off Road	
Surface material	
Type, USCS/other	NA
Mass strength, CI or RCI	0->280
Slope, %	0->70
Obstacle	
Approach angle, deg	90-270
Vertical magnitude, cm	0->85
Length, m	0->150
Width, cm	0->1200
Spacing, m	0->60
Spacing, type	NA
Surface roughness, rms, cm	0-20
Stem diameter, cm } (8 pairs)	0->25
Stem spacing, m } (8 pairs)	0->100
Visibility, m	0->50
Water depth, m	0->5
Water velocity, mps	0->3.5
Water width, m	0->70
Top width, m	0->70
Left approach angle, deg	90-270
Right approach angle, deg	90-270
Differential bank height or differential vertical magnitude, m	0->4
Low bank height or least vertical magnitude, m	0->6
On Road	
Surface material	
Type, USCS/other	NA
Surface strength	
Trails, CI or RCI	0->280
Other, traction coefficients	0.01->0.80
Slope, %	0->70
Elevation, m	0->3000
Surface roughness, rms, in.	0->7.6
Curvature, deg	0-90
Width, m	1->60
Superelevation, %	0->10

Table 4

VEHICLE DATA FOR AMM-75 MOBILITY MODEL

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1. Vehicle Identification

    Payload, Gross Combination weight (as characterized in data following)

2. Running Gear

2.1 Wheeled

- Number of Axle Assemblies:
- For each axle
    - Position (may be mixed with tracks)
    - Operating Load
    - Powered/Unpowered
    - Braked/Unbraked
    - Rim Type, Size
    - Tire Size
        - Tread
        - Construction
        - Rating
        - Rev./Mile
        - Nominal Diameter, OA
            - Width, OA
        - Section Height
            - Width
        - Inflation, Deflection: Sand
            - Cross Country
            - Highway
    - Number of Tires on Axle
        - Duals (Yes/No)
        - Tire Chains Fitted (Yes/No)
    - Central Tire Inflation (Yes/No)
    - Axle Ground Clearance
    - Axle Tread
    - Clearance Between Right-Left Tires

2.2 Tracked

- Number of Track Pair Assemblies

(continued)

(Sheet 1 of 5)

For each pair

Position (may be mixed with wheels)

Operating Load

Powered/Unpowered

Braked/Unbraked

Suspension Type

Track Type (Flexible/Girderized)

Width

Pitch

Grouser Height

Thickness

Single Shoe Road Pad Area

Length on Ground

Number of Road Wheels

Road Wheel Diameter

Hull Ground Clearance

Track Tread

Clearance Between Right-Left Tracks

3. Power Train

Tractive Force-Speed Curve (Optional)

Engine Identification

Maximum Gross HP, RPM

Maximum Gross Torque, RPM

Maximum Net HP, RPM

Maximum Net Torque, RPM

Torque-RPM Curve

Engine-to-Transmission Transfer Gears

Ratios, Efficiencies

Torque Converter (Yes/No)

Identification

Torque Ratio-Speed Ratio Curve

(continued)

Input RPM-Speed Ratio Curve

Input Torque for Above

Converter Accessory Loss Curve

Lockup (Yes/No)

Transmission Identification

Gear Ratios, Efficiencies

Shift Times

Transmission-to-Final Drive Transfer Gears

Identification

Gear Ratios, Efficiencies

Final Drive Identification

Gear Ratio, Efficiency

Acceleration Mass Factors

Overall Gear Ratios, Factors

4. Vehicle Geometry

Overall Dimensions

Length (Combination)

Wheel Base (Prime Mover)

Width

Minimum Ground Clearance (except axles)

Angle of Approach

Departure

Pitch Joint/Fifth Wheel/Pintle (yes/no)

Distance from Front Axle/Road Wheel

Height Above Ground

Center of gravity

For Each Unit and Combination

Height Above Ground

Longitudinal, from Front Axle/Road Wheel

Lateral, from Vehicle CL

(continued)

Table 4 (continued)

Axle/Road Wheel Arrangement*

For each position

Axle Distance fron Front Axle/Road Wheel

Full Bump to Rebound Axle/Road Wheel Travel

Tandem Assembly (No, Dual, Triple)

Other Wheel Positions in Same Assembly

Bogie Axle Distance fron Front Axle/Road Wheel

Mean Spring Rate Between Stops (Two Sides)

Vehicle Bottom Clearnce Profile*

(Approximated by straight lines, specified by x-y coordinates of breakpoints, referenced to axes through Front Axle/Road Wheel Center, positive up and to the rear)

Number of x-y coordinate pairs

x-y coordinate pairs

Other

Height of Bumper/Push Point Above Ground

Height of Driver's Forward Line-of-Sight Above Ground

Maximum Depression of Driver's Forward Line-of-Sight

5. Water Characteristics

Fording Depth, Speed

Swamping Angle, Ingress, Egress

Floater (Yes/No)

Hull Type

Waterline Length

Beam

Draft to Hull Bottom

Minimum Freeboard

Propulsion System Type

Still Water Speed w/o Auxilary Propulsion

Still Water Speed with Auxiliary Propulsion

Width Required to Use Auxiliary Propulsion

Depth Required to Use Auxiliary Propulsion

Bouyancy versus Draft Curve

* Used in obstacle interference and traction module.

(continued)

(Sheet 4 of 5)

Table 4 (concluded)

6. Highway Characteristics (Wheeled Vehicles Only)

   Aerodynamic Drag Coefficient

   Frontal Area

   Cornering Stiffness of Tires (at Highway Inflation and Load)

7. Mobility Assist Systems

   Winch Capacity; Speed

   Pushbar/Bumper Capacity

8. Ride and Obstacle Speed Limits (to one Ride Dynamics Module or Controlled Experiments)

   Number of Absorbed Power Levels

   Ride Speed Limit-RMS Curve for Each Absorbed Power Level

   Impact Speed Limit versus Obstacle Height Curve (Single Obstacles)

      Single Obstacle Height at 15 mph Limit (=HS)

   Impact Speed Limit versus Obstacle Spacing Curve (For Obstacle Height HS)

   NOTE: Requirements for additional data to use AMM-75 2-dimensional ride and obstacle impact simulation to develop above data are given in Reference 6.

9. Obstacle Interference/Clearance and Traction (from Obstacle Interference amd Traction Module)

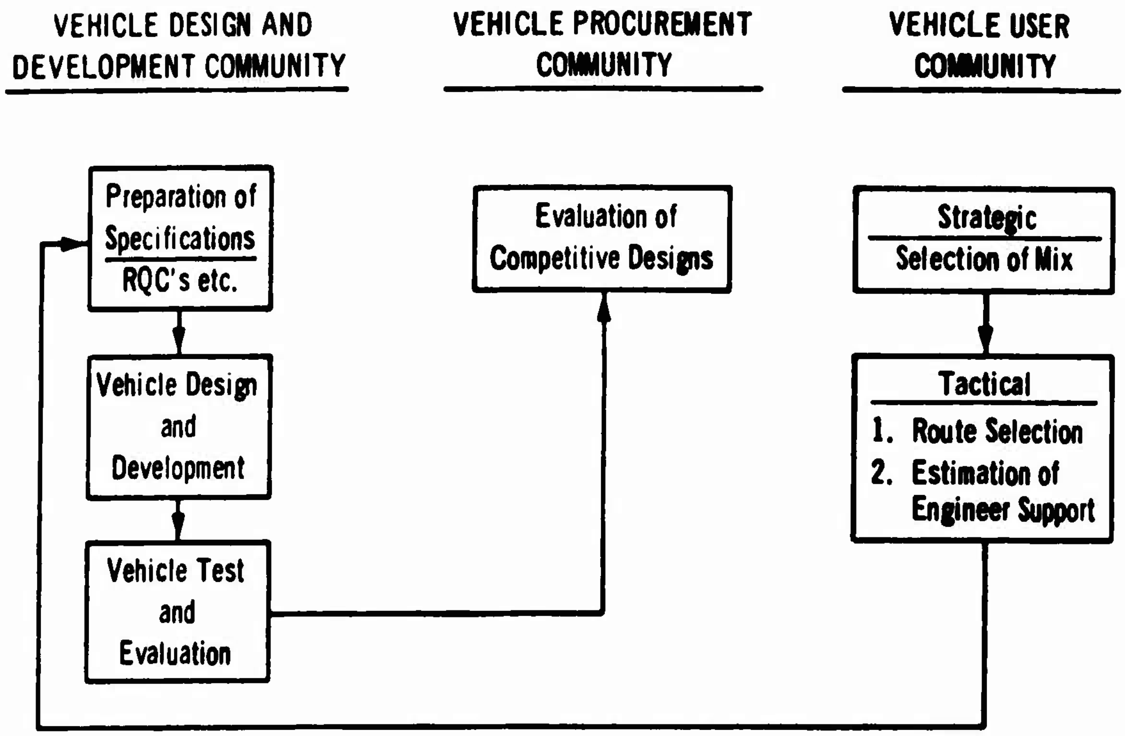
   For Each of 3 or More Obstacle Heights with 3 or More Obstacle Widths with 3 or More Obstacle Approach Angles (27 or more):

      Minimum Clearance During Crossing (Negative = Interference)

      Distance of Critical Clearance Point Behind Front Axle/Roadwheel

      Maximum Traction Required During Crossing

      Mean Traction Required During Crossing



PROSPECTIVE USERS OF VEHICLE PERFORMANCE PREDICTION METHODOLOGY

Figure 1

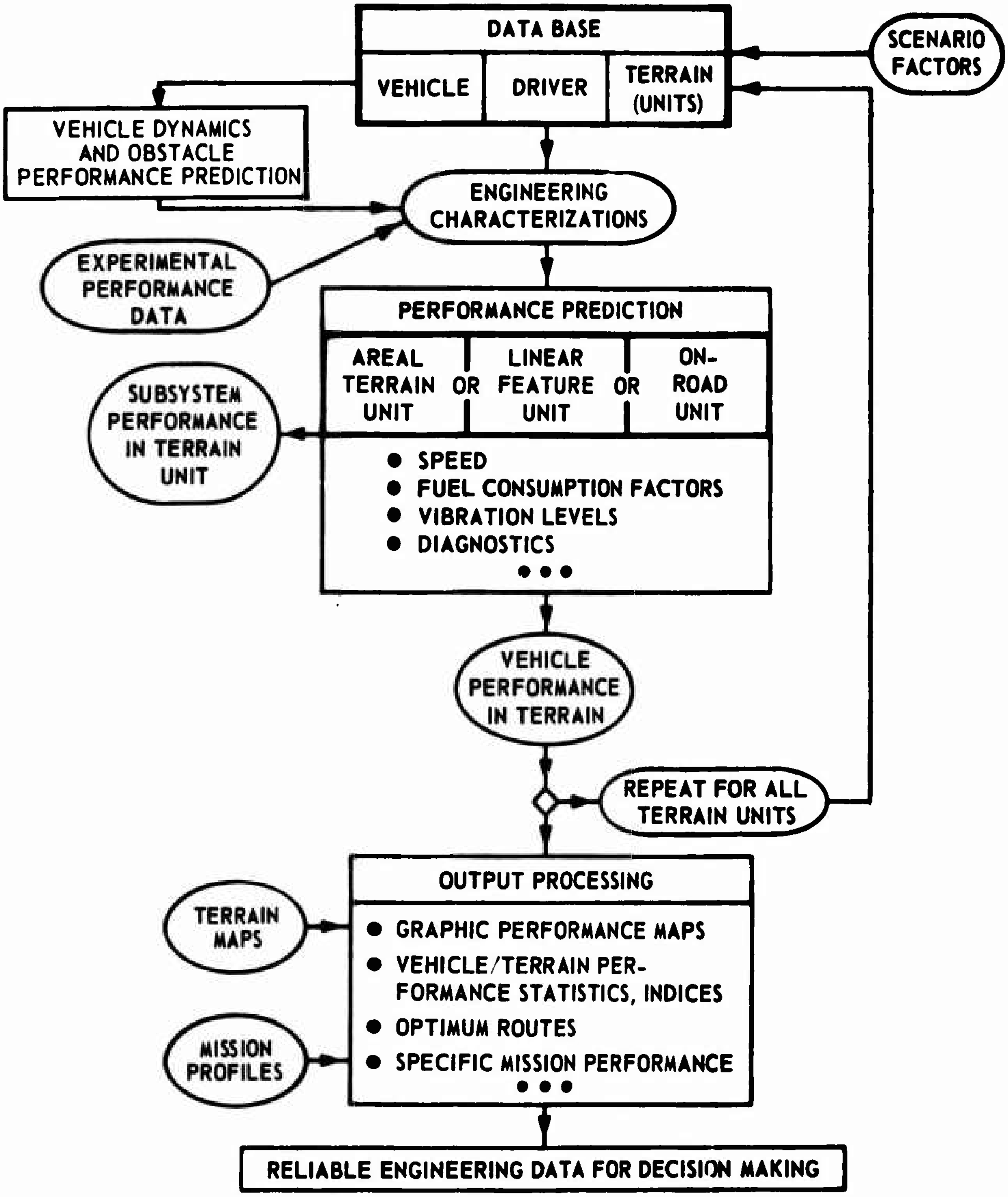
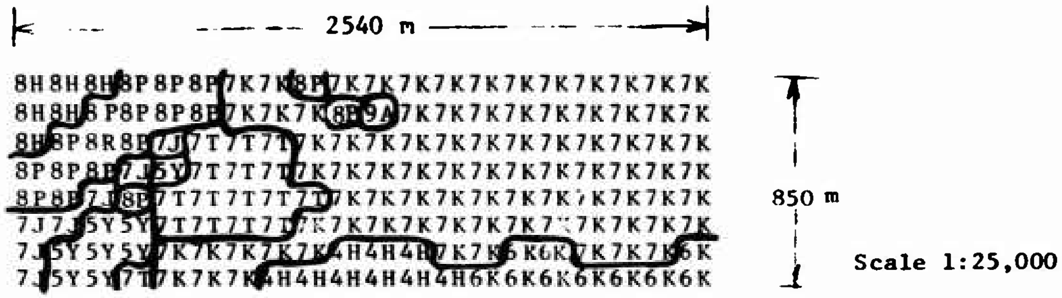


Figure 2. Gross structure of Army Mobility Model



LEGEND		SOIL			OBSTACLES							STEM SPACING								
Patch Number		Type	CI or RCI (Wet-Wet)	Slope, %	Angle, deg.	Vertical magnitude, cm	Width, cm	Length, m	Spacing, m	Spacing type	Surface roughness, in. x 10 cm	Mean spacing (m) of stems having diameter >Y (cm)								Recognition distance, m (Jul-Sep)
												Y 0.2	3	6	10	14	18	22	25	
....	...																			
(4H)	112	2	129	3	138	30	86	1	22	1	7	6	7	15	19	100	100	100	100	11
....	...																			
(5Y)	155	2	103	8	198	46	94	21	5	2	6	1	18	100	100	100	100	100	100	15
....	...																			
(6K)	167	2	111	4	188	33	103	20	24	2	7	6	6	6	7	7	7	7	7	10
....	...																			
(7J)	192	2	133	1	179	10	963	1	60	1	11	5	6	6	8	13	20	100	100	10
(7K)	193	1	114	7	197	46	104	30	56	2	12	5	6	6	20	100	100	100	100	11
....	...																			
(7T)	202	2	129	10	179	10	940	1	60	1	11	6	6	13	20	100	100	100	100	8
....	...																			
(8H)	216	2	130	4	204	30	112	22	32	2	8	6	7	7	7	7	7	7	7	32
....	...																			
(8P)	224	1	102	7	141	53	130	2	26	1	8	7	8	10	17	100	100	100	100	48
....	...																			
(9A)	235	2	125	6	108	43	71	18	29	2	1	5	5	6	7	18	21	100	100	7
....	...																			

Figure 3. Sample terrain factor complex map

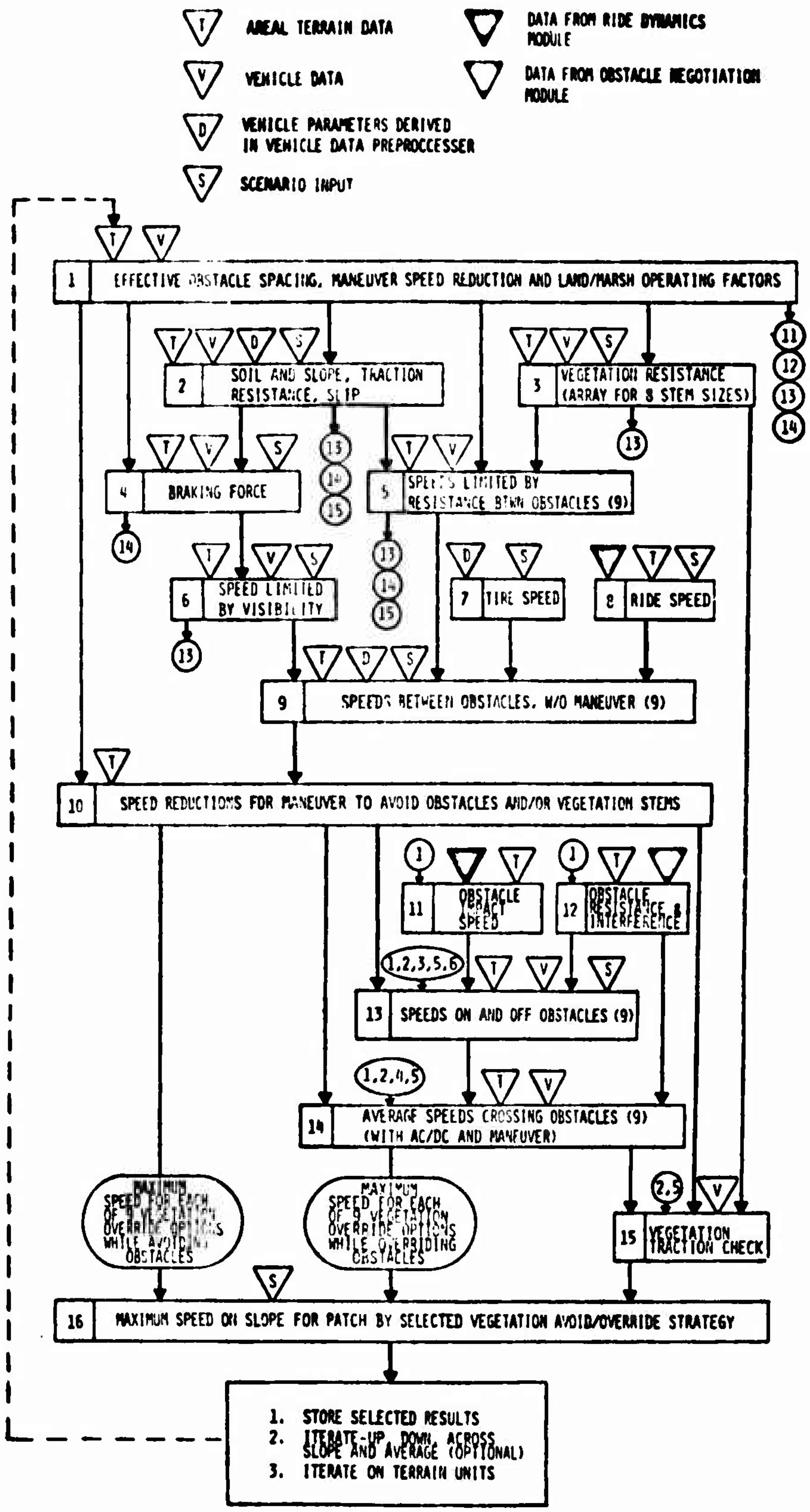


FIGURE 4. GENERAL FLOW OF AMM-75 AREAL MODULE

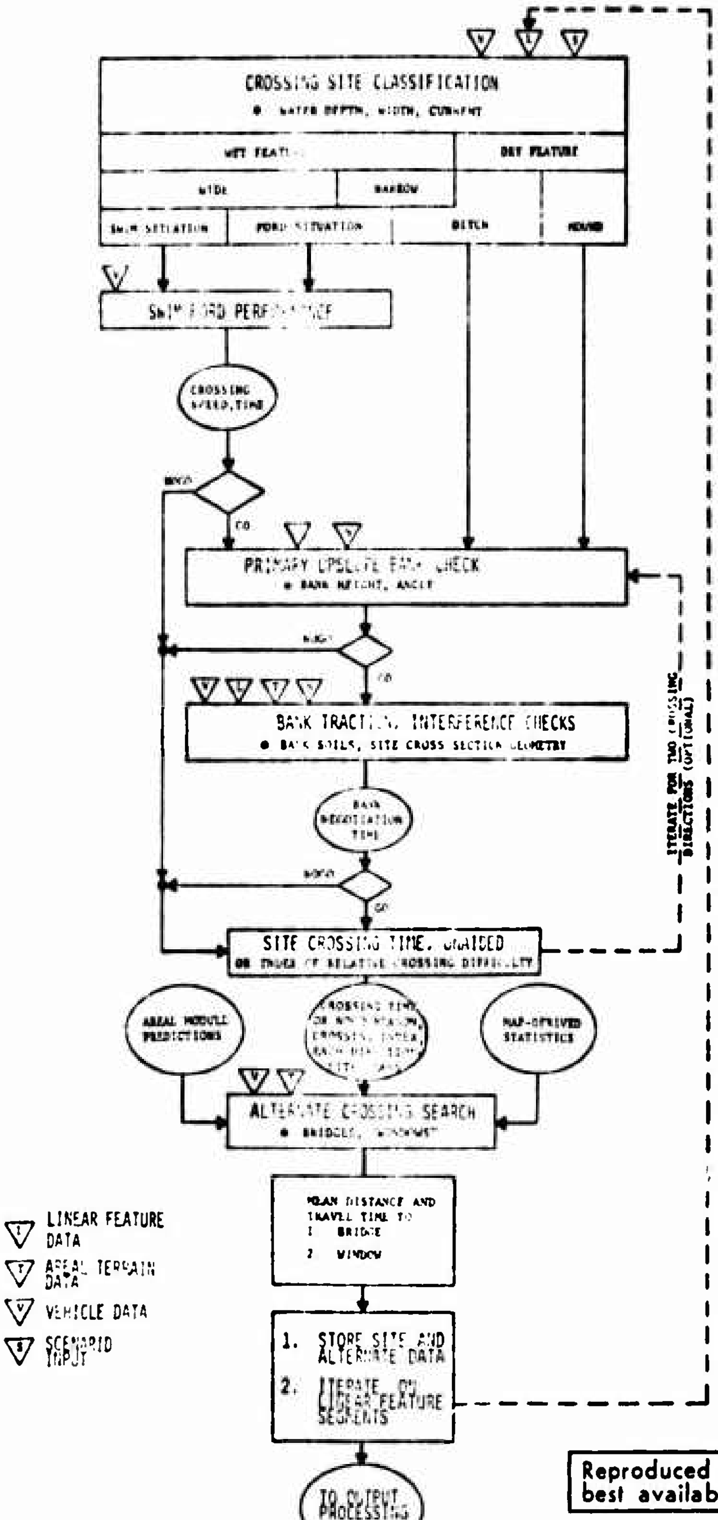
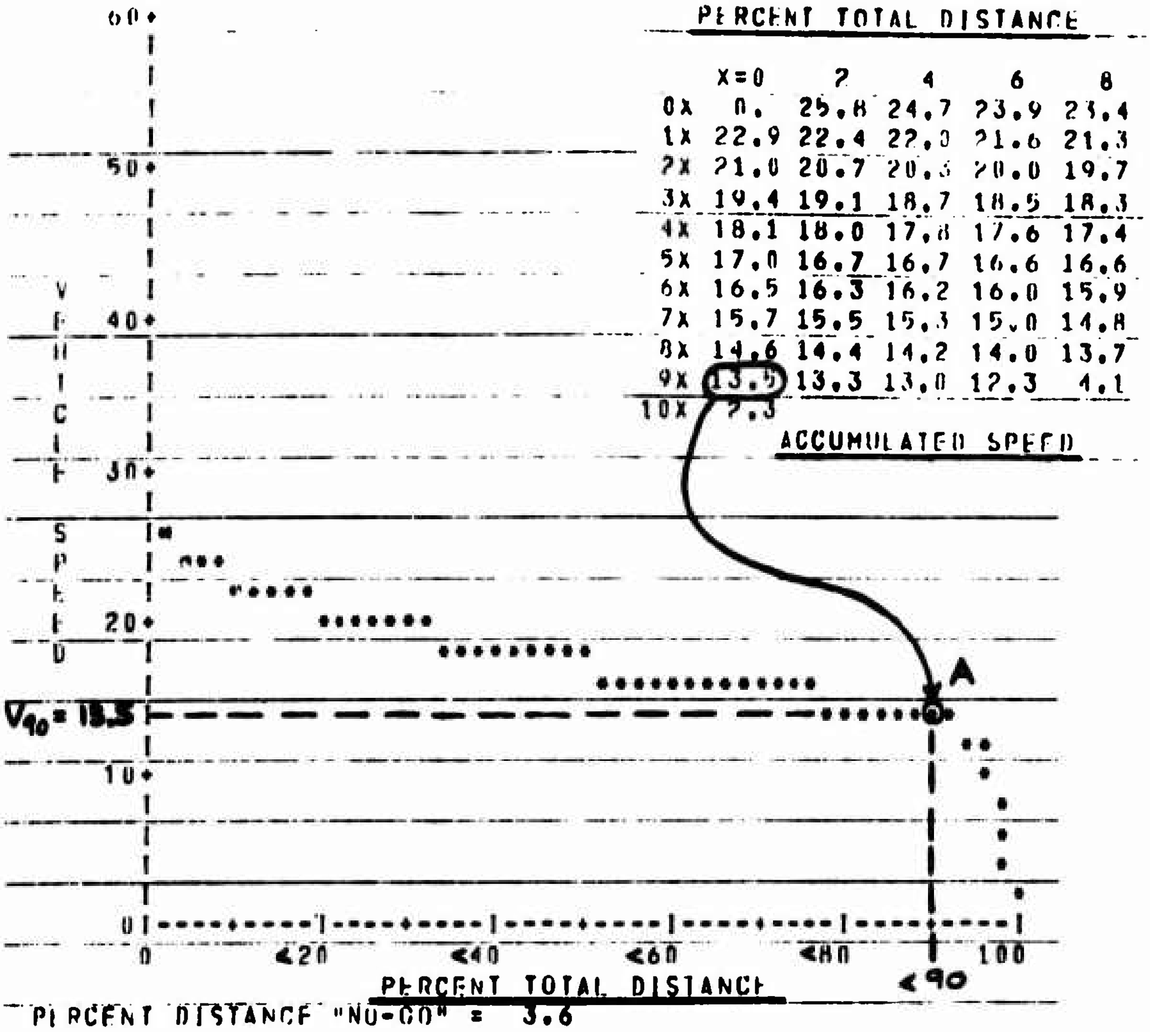


FIGURE 5. GENERAL FLOW OF AMM-75 LINEAR FEATURE CROSSING MODULE

Figure 6. Mobility map of off-road performance of 2-1/2-ton truck speeds in mph



PERCENT TOTAL DISTANCE

	X=0	2	4	6	8
0X	0.	25.8	24.7	23.9	23.4
1X	22.9	22.4	22.0	21.6	21.3
2X	21.0	20.7	20.3	20.0	19.7
3X	19.4	19.1	18.7	18.5	18.3
4X	18.1	18.0	17.8	17.6	17.4
5X	17.0	16.7	16.7	16.6	16.6
6X	16.5	16.3	16.2	16.0	15.9
7X	15.7	15.5	15.3	15.0	14.8
8X	14.6	14.4	14.2	14.0	13.7
9X	13.5	13.3	13.0	12.3	4.1
10X	7.3				

ACCUMULATED SPEED

Figure 7. Mobility profile of off-road performance of 5-ton truck in desert terrain

	FACTOR LIMITING SPEED	% AREA LIMITED	AVERAGE SPEED
(1)	INSUFFICIENT SOIL STRENGTH	0.	-
(2)	INSUFFICIENT TRACTION	0.	-
(3)	OBSTACLE INTERFERENCE	3.6	NO-GO
(4)	COMBINATION OF TERRAIN FACTORS	0.	-
(5)	ROUGHNESS (RIDE) SPEED LIMIT	0.	-
(6)	SOIL/SLOPE RESISTANCES	8.7	10.9
(7)	VISIBILITY LIMIT	0.	-
(8)	MANEUVER PROBLEM	47.9	16.5
(9)	VEGETATION RESISTANCES	9.4	10.8
(10)	AC/DC BETWEEN OBSTACLES	23.9	7.9
(11)	EXTERNAL (URBAN) SPEED LIMIT	6.5	15.5

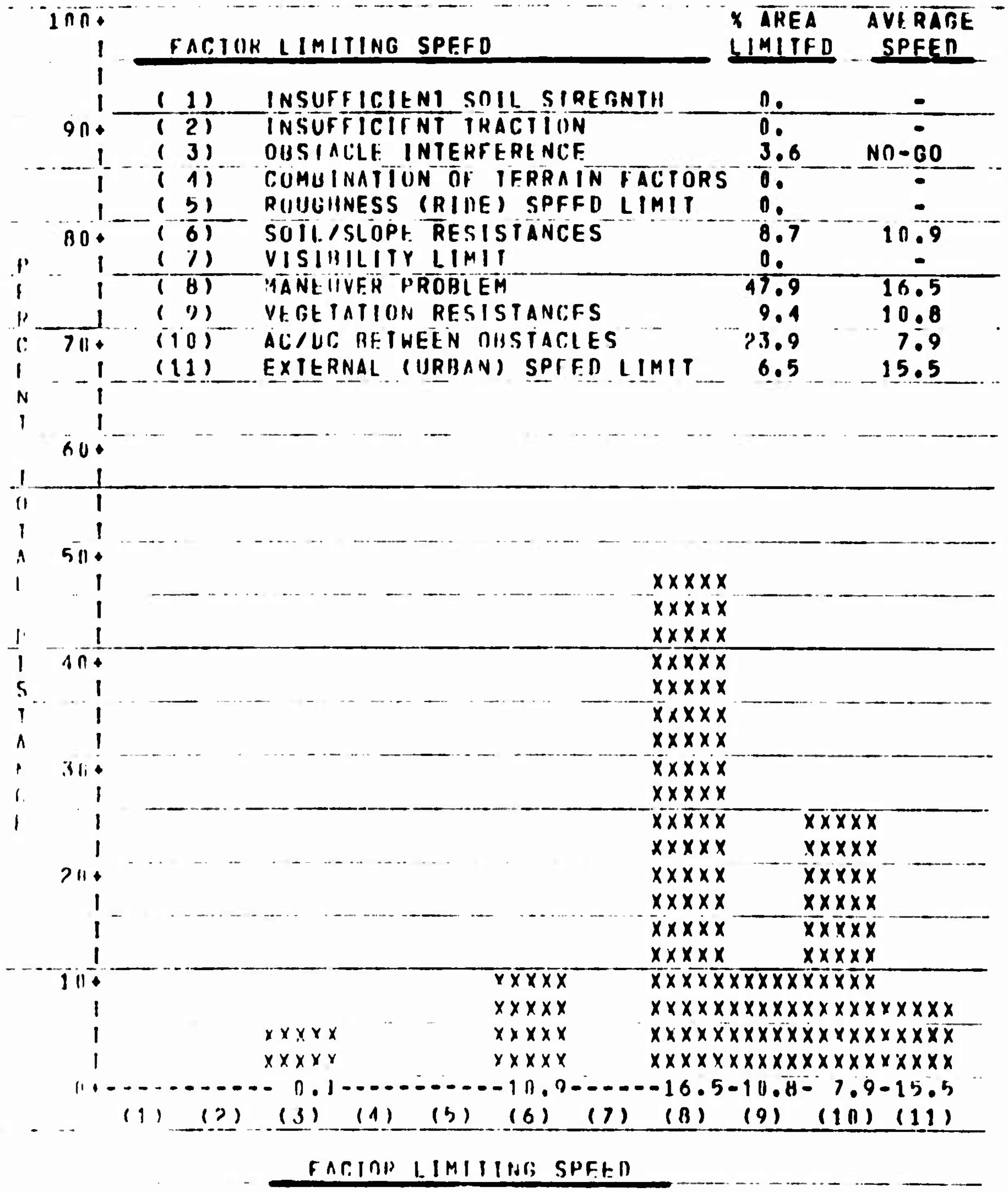


Figure 8. Diagnostic output of AMM-75. Distribution of performance-limiting mobility impediments to 5-ton truck in arid terrain

TERRAIN MODELING TO SUPPORT MOBILITY EVALUATION

by

A. A. Rula and C. J Nuttall, Jr.

Abstract

The Army has been working on terrain modeling to evaluate military mobility since 1971. A major problem in such work is the relationship of the amount of detail incorporated in the modeling process to the credibility of the resulting model for the purposes for which it will be used, as these vary with the nature of the use and the dimensions of the area being modeled. Recent developments have greatly assisted in resolving this problem but much remains to be done. Better methods and techniques are needed to translate available data into factors related to mobility that can be modeled.

Introduction

In 1971 the common needs of the military vehicle design and development, procurement, and user communities for objective analytical means to assess vehicle off-road mobility were recognized and formulated.[1] In the ensuing months the U. S. Army Materiel Command (AMC) mobility research team at the U. S. Army Tank-Automotive Command (TACOM) and the U. S. Army Engineer Waterways Experiment Station (WES) formulated and implemented a first-generation comprehensive ground mobility model, AMC-71.[2]

Successful early applications of AMC-71 and technical developments leading to the release in the near future of the second-generation version of the Army Mobility Model, AMM-75, are discussed in the companion paper before this conference by Jurkat et al.[3]

The ultimate usefulness of any comprehensive computer simulation depends not only upon its flexibility, realism, and credibility, but also on the data base available to support its use in practical studies.

Thus, while there were many problems in formulating the first-generation model, it was immediately recognized that the key to practical success lay in the manner in which terrain is described to the model and represented over specific areas. Two basic considerations were involved in determining appropriate means to provide the terrain required, each imposing seemingly conflicting results.

To treat quantitatively and credibly the many complex vehicle-terrain confrontations possible in the real world, the general terrain description for any point (or small area) has to include deterministic measures of a large number of terrain factors. On the other hand, to make the model practical for application to the study of mobility over geographic areas of sufficient size to be meaningful, the terrain representation has to be consistent with practical considerations for realistic mapping of those factors. Without credible supporting terrain data for areas of practical interest, against which to test vehicles, the model per se would be a mere novelty.

Adoption of the factor complex-mosaic representation of terrain,[4,5] briefly described later, provided the basic answer to the conflicting requirements for terrain representation. As initially implemented to produce terrain data for mobility studies, however, this representation still proved unacceptably costly and time-consuming. As a result, only a few small geographic areas were characterized in time for early applications of AMC-71.

During the past year, work has begun to mechanize, through the use of the computer, the basic processes involved in preparing terrain factor data. Preliminary results have increased the amount of terrain available for study use eightfold and reduced the direct cost of preparing study data for a new area by a factor of ten or more. Moreover, the new data, produced automatically in computer-compatible form, facilitate mobility model predictions and make possible a variety of new output analyses and presentations rapidly and economically.

Terrain Modeling

In determining the effects of terrain conditions on a particular activity, the activity for which performance predictions are desired must be clearly defined, the analytical or mathematical performance prediction model to be used must be identified, and the performance predictions desired must be specified. These considerations dictate the terrain data that must be available for practical problem solution.

AMM-75 predicts vehicle speed and other performance measures within, across, or on a single terrain unit (areal patch, linear feature, or road segment). By making predictions for all terrain units within a geographic area, it, in effect, checks vehicle performance throughout the area.

To make the basic performance predictions, the submodels and algorithms used in AMM-75 require specification of 22 terrain values for each single patch, 10 for each linear feature segment, and 9 for each road segment.*

The kinds and degree of resolution of data required for terrain modeling are not found in any conventional source, especially for areas large enough for the conduct of meaningful mobility exercises. It is necessary to develop the required terrain data from a variety of source materials. The end product is in the form of appropriately coded maps of terrain factors. The terrain factor maps developed are considered to be "study maps," because supporting ground truth data are not such that it can be guaranteed that the specific set of factor values assigned to a given point on the map will in fact be found at that point on the ground. It can be claimed, however, that the maps are consistent with the available information. For example, if source data indicate a forest over some area, appropriate vegetation attributes will be included in the terrain unit descriptions which cover that area.

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* If, as is normally the case, the predictions are to be aggregated in statistical form, or output in map form, additional data on percent of area occupied or geographic location of each terrain unit will be required at the conclusion of all single-terrain-unit prediction runs. These additional data, however, are not a part of the basic terrain data base used by AMM-75 per se.

The Factor-Complex Mosaic Mapping Concept

As noted earlier, the dilemma of deterministic detail versus practical terrain mapping for mobility purposes was resolved by adoption of the factor-complex mosaic mapping concept. In this concept the expanse of any real terrain is represented by a mosaic of areal, linear, or road terrain units, within each of which values of each of the many factors required by AMM-75 are constant within stated tolerances.

Terrain factors

The terrain description system is based on the premise that all attributes of the terrain that are significant to a specific activity can be isolated and measured, and that every location can be described by an array of values that quantify each of the pertinent attributes.[4,5] These attributes (e.g. slope, plant stem diameter, etc.), called terrain factors, are the basic building blocks of the system. Conceptually, a value (e.g. 5 percent slope) is assigned to each terrain factor for all points within a mapped area. Terrain factor values are grouped in classes (e.g. 5-10 percent slope) that represent a compromise between resolution and the practicalities of measurement and mapping in the real world. For convenience, the numbers for each factor are arranged so that the lowest numbers have the least effect on mobility and the high numbers have the greatest effect.

Terrain factor families

For convenient handling of mapped information, two or more terrain factors that are related in their characteristic effect on a given activity may be grouped together as a terrain factor family. Four factor families describe terrain for mobility purposes--surface composition, surface areal geometry, vegetation, and surface linear geometry. These terrain factor families and related terrain factors are discussed in the following paragraphs.

Surface composition. The surface composition terrain factors that have the most significant effect on ground mobility are the type of surface material and strength of the surface layer to a depth that

depends upon type of material, vehicle characteristics, and volume of traffic to be imposed. The type of surface material is established by using the Unified Soil Classification System (USCS)[6], which, in turn, establishes the soil strength descriptor and soil depth to be used to relate soil strength to pertinent vehicle performance parameters. Soil strength measurements are given in terms of cone index or rating cone index;[1] the former is used in clean sands and the latter in clayey, silty, and organic soils. In AMM-75, fat clays are distinguished from other fine-grained soils for purposes of soil slipperiness calculations.[3]

Strength of a soil depends on its moisture content. Accordingly, mobility performance predictions depend on seasonal soil wetness. The terrain data usually include soil strengths appropriate to several seasonal wetness conditions (selection of the appropriate value is made by the model based on input specifications). To establish these for a given area, a typical day-by-day rainfall record which duplicates long-term rainfall statistics for the area is used in a soil moisture-strength prediction model.[7] This model relates gains or losses of soil moisture to soil type, season, rainfall, and drainage factors. These, in turn, are related to soil strength for those layers significant to mobility.

Surface areal geometry. A uniform area from the viewpoint of surface areal geometry is one in which the characteristic slope, in percent, surface roughness, and the size, spacing, and continuity of a recurring characteristic mobility obstacle are constant. The characteristic obstacle, which might represent such features as logs, boulders, small ditches, or stumps, is described by its approach angle, vertical magnitude, length and width, representative spacing, and a statement concerning its continuity (linear or random). Surface roughness is described in terms of statistical parameters of the surface microprofile.

Vegetation. Vegetation factors that have a significant effect on ground mobility are those that describe the vegetation structure and the screening characteristics of plants or plant assemblages. The physical attributes used to describe structure are stem size and stem spacing.

Screening, or visibility, is the distance at which a vehicle operator can recognize an obstacle of potential mobility significance, measured along a selected line of sight. Seasonal variations in visibility may be included.

Surface linear geometry. This factor family is designed to describe discrete, linear, convex features of the earth's surface, such as embankments, dikes, etc., and discrete concave features, such as streams, large ditches, road cuts, etc. Size and shape of linear features are characterized by a profile constructed at right angles to the terrain feature.

Water depth and water velocity are time dependent factors that are generally defined in terms of maximum, minimum, and mean values.

Grouping of terrain or road factors

The grouping of terrain factors and factor families to construct terrain (areal and linear) and road units for mobility purposes is outlined in Figure 1. The end products of this process are maps. Appropriate groups of factor families are combined to construct three types of terrain units, areal, linear, and road. Surface composition, surface areal geometry, and vegetation factor families describe areal terrain units. They appear as discrete areas or "patches" on an areal terrain unit map. Surface composition and surface linear geometry are combined to describe linear terrain units, which appear as lines on a terrain unit map because of their characteristic length and relatively narrow width (i.e. streams, road embankments, etc.). Surface composition and a special surface geometry factor family are used to describe road units, which also appear as lines on a terrain map.

Preparation of Terrain Maps

The submodels of AMM-75 that predict vehicle performance not only dictate the terrain factors required, but also establish the range over which each factor has a significant effect. The significant range of each factor is subdivided into factor value classes.

In establishing the number and ranges of class intervals, mapping problems are minimized by avoiding detail that is not significant to vehicle behavior. For example, slopes beyond 70 percent are essentially impassable to current vehicles, so that definition above this level serves no useful purpose. A listing of the terrain factors, their usual units, factor ranges, and the number of classes into which each factor is divided for the establishment of terrain unit boundaries is given in Table 1.

The first terrain study maps for mobility evaluation purposes were prepared manually, in large part from air photos. Single-factor maps were made by air-photo interpretation, and subsequently overlaid to produce factor family maps. The procedure required skilled air-photo interpreters who understood vehicle mobility fundamentals. The optimum combination of required talents was not always available in practice. In addition, the process was slow and costly, and the manually produced maps did not lend themselves to reliable computer manipulation during either their construction or their later use.

The original process has recently been revised to use the computer extensively from development of the terrain unit maps right through to the production of mobility maps. The concept of the computer-oriented procedure is essentially the same as the manual procedure.

Manual procedure

Separate maps are prepared manually for each terrain factor at a common scale (usually 1:25,000 or 1:50,000). The boundaries of terrain factor classes (except slope classes, which are normally obtained from topographic maps) are established on aerial mosaics using air-photo interpretation techniques, and subsequently transferred to a map of the appropriate scale. Where ground truth data are available, the sampling points are located on the mosaic and described by the observed terrain factor complex number. For each individual factor or factor family, patterns on the photographs are identified by differences in tone, texture, and geometry. For areas and patterns for which there are no ground truth data, factor classes are assigned by associating land

use, landform, topographic position, and the interpreter's background knowledge of the area.

The final step in the mapping procedure is the construction of terrain factor complex, or terrain unit, maps by superposition of factor or factor family maps. At this stage, each final map unit is identified by a sequence of terrain factor class numbers. Using these numbers, the terrain units are ordered by increasing general mobility difficulty, and assigned identification numbers in this order. Factor maps of an area at Fort Knox are shown in Figures 2-4; an illustration of a terrain factor complex map for the same area, together with the number array that describes some of the units shown on the map, is given in Figure 5.

A computer-aided technique

To construct reasonable mobility maps for large, new study areas on a timely basis, a second approach was designed. This approach begins by assembling available information in map form on many physical aspects of the area, i.e. soils, geology, gross vegetation, etc., plus the best available topographic maps. Numeric codes are established for all information in the legend of each map.

By overlaying the several maps at a common scale, they are consolidated into a single map with appropriately expanded legend information. This step is currently implemented on the computer. To do this, discrete areas (or line segments) on each basic map are defined in a manually prepared overlay and legend information in coded form. In the case of normal topographic maps, information density is so great that two overlays are made; one to extract basic slope data, and a second to extract all of the extensive land-use and other useful information which is overprinted on the contours. Figure 6 illustrates a coded land-use map made by manually overlaying a topographic map. The coded legend picks up all information provided in the original map legend for each discrete area.

Boundaries between differently coded areas on the separate manual overlays are defined by a series of x-y coordinates automatically generated by a digital line-follower, and recorded, with the codes, on a

magnetic tape. Computer routines convert these data to a new map, stored as a computer array, in which each discrete area is approximated by a large number of rectangular cells of predetermined size, and each cell is associated with the appropriate basic data in coded form. Figure 7 shows the map in Figure 6 as output by the computer using 106- by 127-m cells. This cell size permits preparing maps at a scale of 1:25,000 by using a high-speed printer and two characters per cell.

When the manual overlay data for all individual maps are in the computer, they are then overlaid (by various routines) to produce the final consolidated map and corresponding extended legend, again stored in arrays (Figure 8). At this point in the process the map consists of a mosaic of small areas, within each of which all descriptors from the available data are identical. These areas are logical areal terrain units or patches by basic definition, since there are no data upon which to assign anything other than a single set of mobility factor values throughout any one of them.

In the final step, the composite qualitative legend information for each patch is interpreted to assign a reasonable, consistent set of quantitative terrain factor classes to the patch. This is done by examining appropriate subsets of the qualitative information and inferring from each, class values for specific single terrain factors or factor families. Because of the discrete values in the composite legend data, these interpretations can be coded as algorithms and formed into a computer routine for translating the coded qualitative legend directly into quantitative terrain factor classes. Design of the translation routine makes use of many additional data sources, including air photos of areas of special interest or complexity. Separate routines are used for different geographic areas to reflect appropriate climatic and cultural influences and kinds and quality of the available basic map data.

When the qualitative composite map legend data have been translated, as above, the result is a terrain factor complex, or patch, map containing all of the terrain data for the mapped area that are needed for AMC-71 or AMM-75. Moreover, the map and all of the data are immediately available in

the computer for making vehicle performance predictions, statistical aggregations of performance in the area, performance maps such as shown in Figure 9, etc.

Assignment of terrain factor values

The mobility modules use actual values for the numerous factors rather than class designators. In the past, the value assigned was always the midrange value for the class specified. This interpretation of the classed data, in effect, replaces nature's continuum by a step function, which has some undesirable side effects when large parts of a study area are nominally similar, and hence fall within a single terrain-unit definition. At present, numerical values for each terrain factor in a specific patch are assigned random values within each designated class range describing the patch. Thus, two patches that are identical at the terrain unit level are no longer necessarily identical at the patch level. This final step in assigning terrain factor values to the map is done only once to complete the map legend. When the legend is completed, all vehicles subsequently see each individual patch in terms of an identical array of numerical values for the terrain factors describing it.

Comparison of the Manual and Computer-Aided Terrain Mapping Techniques

Figure 10 compares the general flow of processes and information generation by the two mapping procedures. Differences arise primarily from the form of the basic data with which the two processes begin. When starting with the more detailed but unanalyzed air-photo information, terrain factor maps are developed directly, and patches are defined by their subsequent overlay to form a factor complex map. When beginning with mapped information, which already represents a considered analysis of the situation, the mapped data are first consolidated by overlay to a single map of all information to be used. Patches are assigned on the basis of apparent uniformity shown at this point, and terrain factor sets are assigned patch-by-patch on the basis of the total information.

The result in each case is a map in the terms needed to study vehicle mobility in the area using AMC-71 or AMM-75.

The primary advantages of the computer-aided method are that it meets demands for relatively rapid preparation of terrain and mobility data for a variety of large study areas at a reasonable cost. This is accomplished by starting from mapped data rather than beginning with air-photo interpretation. Available map legend information lends itself to consistent computer interpretation, and both manpower and personnel skill requirements are accordingly considerably reduced.

On the other hand, the resolution and accuracy of maps generated by the computer-aided technique depend heavily on the quality of available map information, consistency in map scales and legends, and the realism of the relations by means of which the standard map legend information is translated to terrain factor classes. At present the preliminary relations that have been developed provide terrain factors that are consistent with the available basic mapped data. The relations appear reasonable based on air-photo spot checks and on extensive experience with vehicle tests and terrain measurements in the field. They are totally unvalidated, however. Work is needed to validate and refine or modify these relations, and to develop a reliable standard methodology for this critical part of the computer-aided technique.

Terrain Data Available for Ground Mobility Studies

Only a few relatively small areas of the world are presently mapped explicitly in terms of the terrain factors used in AMC-71 and AMM-75. From 1971 to 1974, five small areas, each approximately 3 by 50 km were mapped at a scale of 1:25,000 by the manual, air-photo method to obtain a variety of terrain data to exercise the developing mobility model and to assess the practical aspects of the mapping method. Some of these long, narrow terrain samples, termed transects, were used in early vehicle mobility evaluation studies.[8,9] The transects, for which both areal and linear feature terrain unit maps are available, are representative of a variety of physical environments as follows:

Identification	Location
West Germany*	Near Stuttgart
Arizona*	Yuma Test Station
Thailand*	Near Nakhon Sawan
Puerto Rico	Near Arecibo
Alaska	On North Slope
South Korea	Near Taejon

In a recent vehicle mobility evaluation,[10] 1:50,000 study maps were made for two areas, each about 30 by 100 km, using the computer-aided terrain factor mapping technique. In addition, a number of much smaller areas have been mapped by ground measurements in conjunction with AMC-71 validation tests and some special vehicle evaluation tests. These data sets are identified in Table 2.

Finally, there are available data from which high-quality, large-scale terrains maps for mobility purposes could be readily prepared for several additional areas in West Germany and Thailand. The locations and approximate sizes of these areas are as follows:

Location	Approximate Size mi^2	Approximate Size km^2
West Germany		
Baumholder	15	39
Bergen Hohne	10	26
Grafenwohr	10	26
Thailand		
Nakhon Sawan	965	2499
Lop Buri	1100	2849
Chiang Mai	770	1994
Pran Buri	575	1489
Khon Kaen	575	1489
Chanthaburi	770	1994
United States		
Fort Hood	95	246
Fort Carson	42	109
Fort Riley	69	179

*Partial road-unit maps also available.

The West Germany and United States areas are on military reservations. A variety of terrain conditions in Thailand range from coastal plains in Chanthaburi to mountains and valleys at Chiang Mai.

Concluding Remarks

In spite of growing demands for the kind of reliable quantitative mobility information that the Army Mobility Model can supply there are no programs or plans specifically to extend the current limited terrain data base or to develop rational procedures to do so on a timely and cost-effective basis. The computer-aided mapping technique discussed herein was developed as part of an ad hoc study. The discussion that follows tells what is needed and, hopefully, what will eventually happen. At present, it seems that only a few elements of the mobility R&D community consider that these needs are in any way urgent.

Any overall plan to improve the quality and utility of terrain modeling to support mobility evaluations must include means of standardizing, simplifying, and validating end products (terrain maps), increasing the readily available data base, and developing means for meeting unexpected user requirements on a timely basis. All of these must be achieved at a reasonable cost.

Foremost among these at this time is the need to expand the present terrain data base. Although the Army Mobility Model is maintained by WES and TACOM at a high state of readiness, its value in quick-response situations is limited because the terrain data base is often inadequate or inappropriate at the time the need arises. For an increase in the demonstrated value and utility of the Army Mobility Model, the current terrain data base must be increased. Too often questions are asked about vehicle performance in environments for which mobility terrain characterization is not now available.

The next priority is new work to develop methods and techniques for rapidly and economically translating available maps and other data into terrain factor values related to vehicle mobility, and for preparing

such information for input to engineering models for the prediction of terrain-vehicle-driver interactions at various degrees of resolution. Credibility demands that acquisition and interpretation of such information be done consistently and that the latter be done on the basis of demonstrable relations among quantities required for mobility prediction and the available qualitative site descriptors. Consistency, timeliness, and economy together demand that the process be computer oriented insofar as possible.

Corollary to the inherent high resolution of the Army Mobility Model and its data requirements are time and cost constraints on the size of an area that can, in fact, be used in a given practical study. These constraints generate the need for means to examine mobility over much larger areas and at suitably reduced scales and performance resolutions in order to interpret the details of smaller area results properly in the context of a more general situation. To be meaningful, such lower resolution methods for terrain characterization and for related performance predictions must produce mobility assessments over any given area which are logically and statistically consistent with assessments that would result from the full detailed study of the same area.

Intelligent prosecution of these priority tasks in something less than a "fire-drill" atmosphere would necessarily involve the solution of a number of longer-range problems, such as the development and validation of standardized procedures for interpreting, analyzing, and processing terrain data from multiple sources of various levels of resolution. Although optimum terrain factors and factor classes depend on user needs and resulting model applications, continuing expansion in the use of the model, which the developing data base would foster, would almost automatically answer many questions in this area.

It should not be the intent of any future program to establish a large ground truth data collection program. Rather, the aim should be to establish and immediately apply rapid, economical, standard methods for processing and interpreting available terrain data as the need arises. The computer should be employed as much as possible to facilitate

data processing. To be cost-effective, the resulting methods must be structured on the basis of available data. Once terrain maps are prepared from available data, a well-planned validation program requiring a minimum amount of ground truth should be implemented. In addition, development and demonstration of accepted methods of meaningfully comparing terrain on the basis of single or combined attributes and/or effects (performance) should be prosecuted to allow determination of whether or not any existing terrain data set can reasonably be used in new situations. The minimum area that must be mapped to be effective for various categories of use must also be established.

To meet two of the most urgent user requirements--economy and quick answers--a survey of the entire system must be made to introduce automated procedures wherever feasible.

A simplified version of the AMC-71 mobility model, suitable for use with low-resolution generalized terrain data, and the comprehensive AMM-75 model using detailed terrain data are presently on hand to meet basic user requirements for vehicle mobility assessment. Plans for the future development of these models should include adjusting and extending them as necessary so that they can be interfaced with higher-order models involving scenarios ranging from individual small-unit actions to division-size engagements. It is already apparent that future R&D plans must include development of clear procedures for interfacing pertinent models and supporting terrain data. This implies that a coordinated effort with the combat developments community, whose responsibility it is to establish policies and procedures for the development and use of standard scenarios in present and future combat developments processes, is in order.[11] It also implies that mobility-oriented terrain studies should be coordinated with the agencies responsible for production mapping to standardize map legends more meaningful to mobility evaluation studies. Improved mobility simulation would aid in a better assessment of the capability of current and future Army forces.

Validation is required in each step just discussed. Simplification, standardization, and automation can and should lead to lower cost, and increasing the data base and interfacing with higher-order models will satisfy additional user requirements. A true measure of cost effectiveness is not obtainable, however, until the question "How good are the end products?" can be answered. This means validation with ground truth data and real vehicles in real terrain in real time.

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Table 1

Summary of Terrain Data Required for Army Mobility Model

Terrain or Road Factor	Range	No. of Factor Classes
Off Road (Areal)		
Surface material		
Type, USCS/Other	NA	5
Mass strength, CI or RCI	0->280	11
Slope, %	0->70	8
Obstacle		
Approach angle, deg	90-270	14
Vertical magnitude, cm	0->85	7
Length, m	0->150	7
Width, cm	0->1200	5
Spacing, m	0->60	8
Spacing, type	NA	2
Surface roughness, rms, cm	0-20	9
Stem diameter, cm } (8 pairs)	0->25	8
Stem spacing, m } (8 pairs)	0->100	8
Visibility, m	0->50	9
Off Road (Linear)		
Water depth,* m	0->5	6
Water velocity,* mps	0->3.5	6
Water width,* m	0->70	21
Top width, m	0->70	21
Left approach angle, deg	90-270	20
Right approach angle, deg	90-270	20
Differential bank height or differential vertical magnitude, m	0->4	9
Low bank height or least vertical magnitude, m	0->6	8
On Road		
Surface material		
Type, USCS/Other	NA	5
Surface strength		
Trails, CI or RCI	0->280	11
Other, traction coefficients	0.01->0.80	8
Slope, %	0->70	8
Elevation, m	0->3000	7
Surface roughness, rms, cm	0->8.1	9
Curvature, deg	0-90	10
Width, m	1->60	10
Superelevation, %	0->10	4

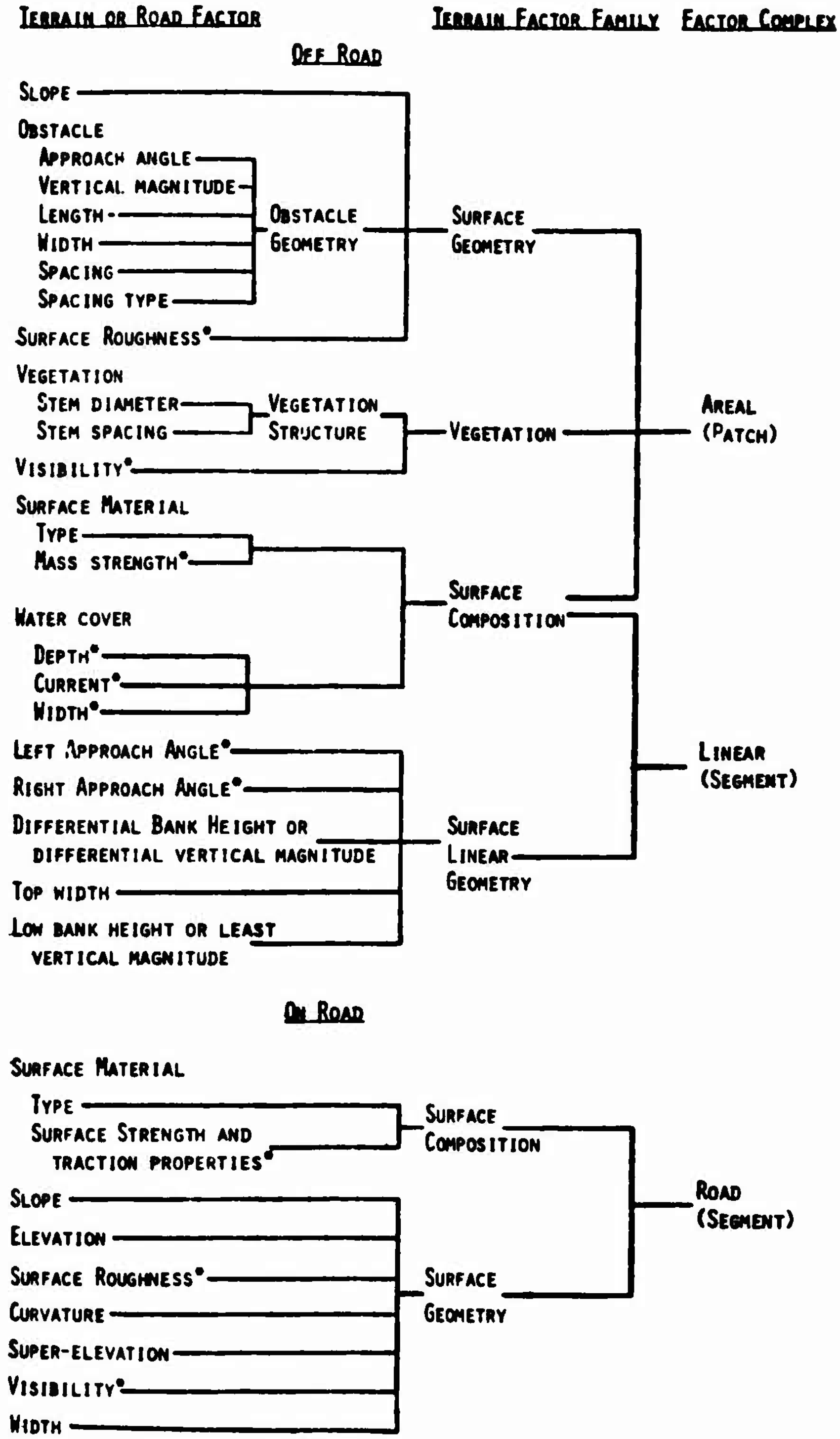
*Also used in areal terrain (when lakes or marshes) are encountered.

Table 2

Terrain Data Available in AMM-75 Format

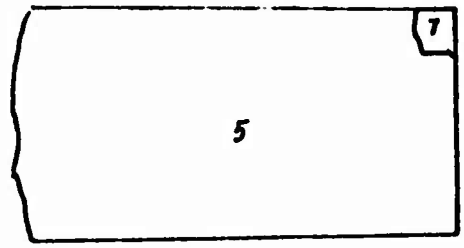
Identification	Location	Size*
	Off Road	
Fort Knox 1	At Fort Knox, Kentucky	6.2 mi^2 (16 km^2)
Fort Knox 2	At Fort Knox, Kentucky	4.7 mi^2 (12 km^2)
Fulda Strip**	Near Freiensteinau, West Germany	9907 ft (3020 m)
Fulda Strip**	Near Saltz, West Germany	6153 ft (1875 m)
Oklahoma Strip (4) +	At Fort Sill	approx 9 mi (14.5 km)
Arizona Strips (4) +	At Yuma Test Station	Approx 4 mi (6.4 km)
Florida Strips (3) +	At Eglin AFB	Approx 3 mi (4.8 km)
Michigan Strips (3) +	Near Houghton	Approx 3 mi (4.8 km)
HIMO, Europe	West Germany	Approx 1408 mi^2 (3646 km^2)
HIMO, Middle East	Jordan	Approx 1056 mi^2 (2735 km^2)

* Transect area or traverse length.
** Special mobility studies.
\+ Validation tests. Numbers indicate number of cross-country traverses.



* Complete data for an area may include several values for any or all of these quantities representing seasonal variations. At run time appropriate value(s) are selected by the run specification.

Figure 1. Construction of terrain or road units



Scale 1:25,000

LEGEND (partial)

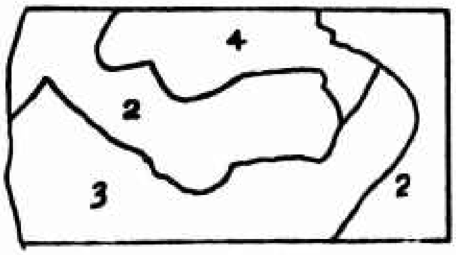
MAP UNIT*	SOIL TYPE*	SOIL STRENGTH*
5	1	5
7	1	7

* Each map unit represents an array of two symbols indicating soil type and soil strength.

Mapping class ranges for soil type and soil strength are:

SOIL TYPE		SOIL STRENGTH	
FACTOR CLASS	TYPE	FACTOR CLASS	CI or RCI
1	Fine grained soil, CH	1	>280
3	Coarse grained soil	2	221 - 280
4	Muskeg	3	161 - 220
		4	101 - 160
		5	61 - 100
		6	41 - 60
		7	33 - 40
		8	26 - 32
		9	17 - 25
		10	11 - 16
		11	0 - 10

Figure 2. Surface composition factor family map

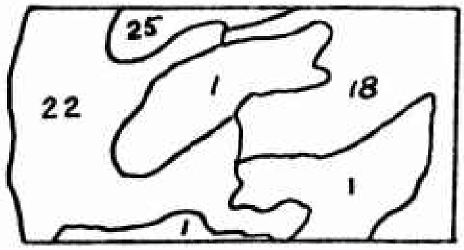


Scale 1:25,000

LEGEND

FACTOR CLASS	SLOPE, %
1	0 - 2
2	2.1 - 5
3	5.1 - 10
4	10.1 - 20
5	20.1 - 40
6	40.1 - 60
7	60.1 - 70
8	>70

Figure 3. Slope factor map (single factor)



Scale 1:25,000

LEGEND (partial)

MAP UNIT*	OBSTACLE APPROACH ANGLE**	OBSTACLE VERTICAL MAGNITUDE**	OBSTACLE WIDTH**	OBSTACLE LENGTH**	OBSTACLE SPACING**	OBSTACLE SPACING TYPE**
1	1	1	1	1	1	1
18	13	2	5	6	3	1
22	14	6	3	6	5	1

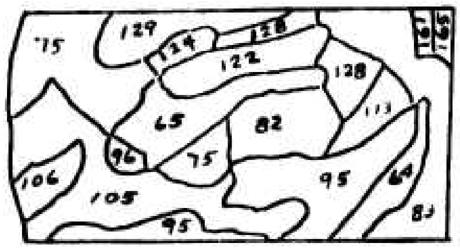
LEGEND (partial)

* Each map unit represents an array of six symbols indicating mapping classes of obstacle approach angle, obstacle vertical magnitude, obstacle length, obstacle width, obstacle spacing, and obstacle spacing type.

** Mapping class ranges for each factor used in describing obstacles are:

OBSTACLE APPROACH ANGLE		OBSTACLE VERTICAL MAGNITUDE		OBSTACLE WIDTH		OBSTACLE LENGTH		OBSTACLE SPACING		OBSTACLE SPACING TYPE	
FACTOR CLASS	DEG.	FACTOR CLASS	CM	FACTOR CLASS	CM	FACTOR CLASS	M	FACTOR CLASS	M	FACTOR CLASS	TYPE
1	178.6 - 180.0	1	0 - 15	1	>120	1	0.0 - 0.3	1	Base	1	Random
2	180.0 - 181.5	2	16 - 25	2	91 - 120	2	0.4 - 1.0	2	20.1 - 60.0	2	Linear
3	175.6 - 178.5	3	26 - 35	3	61 - 90	3	1.1 - 2.0	3	11.1 - 20.0		
4	181.5 - 184.5	4	36 - 45	4	31 - 60	4	2.1 - 3.0	4	8.1 - 11.0		
5	170.1 - 175.5	5	46 - 60	5	0 - 30	5	3.1 - 6.0	5	5.6 - 8.0		
6	184.5 - 190.0	6	60 - 85			6	6.1 - 15.0	6	4.1 - 5.5		
7	158.1 - 170.0	7	>85			7	>150	7	2.6 - 4.0		
8	190.1 - 202.0							8	0.0 - 2.5		
9	119.1 - 158.0										
10	202.1 - 211.0										
11	135.1 - 149.0										
12	211.1 - 225.0										
13	90.0 - 135.0										
14	226.0 - 270.0										

Figure 4. Obstacle factor map (multiple factors)

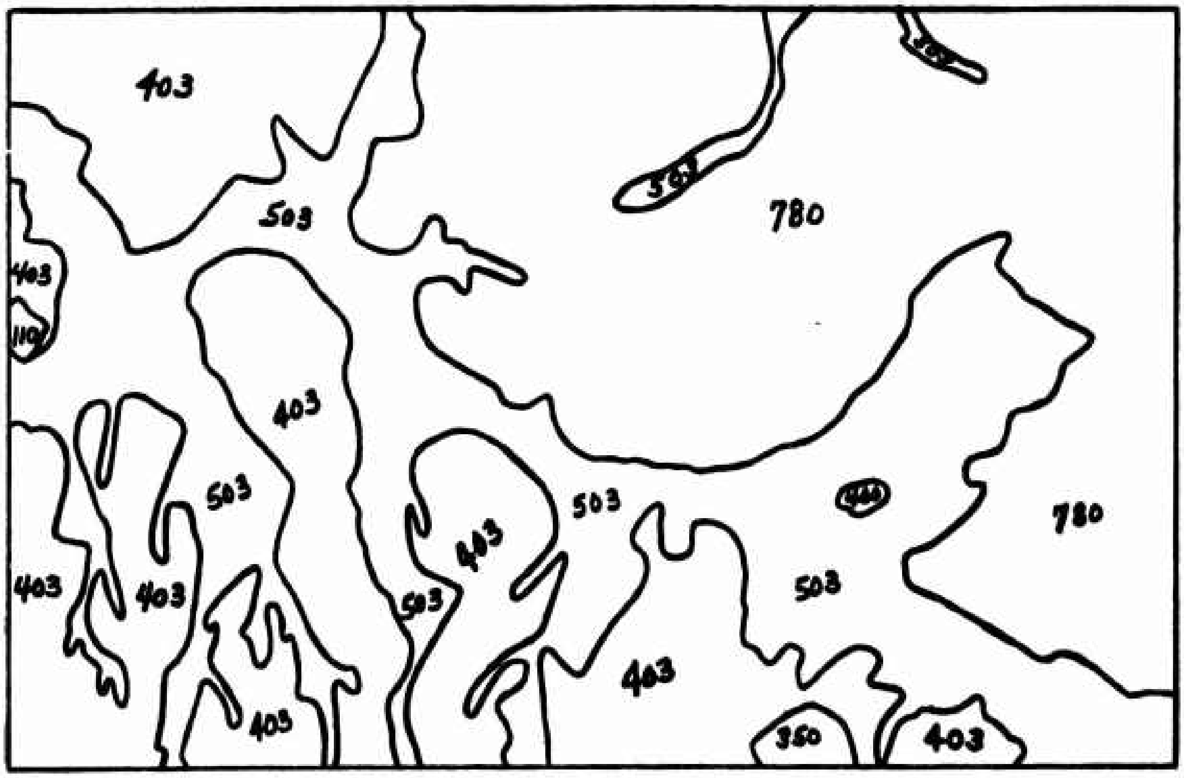


Scale 1:25,000

LEGEND (partial)

TERRAIN UNIT	SURFACE TYPE	SURFACE STRENGTH	SLOPE	OBSTACLE: APPROACH ANGLE	OBSTACLE: VERT. MAGNITUDE	OBSTACLE: WIDTH	OBSTACLE: LENGTH	OBSTACLE: SPACING	OBSTACLE: SPACING TYPE	SURFACE ROUGHNESS	Spacing of Stems Equal to or Greater than Given Stem Diameter Class: 1	2	3	4	5	6	7	8	RECOG DIST.
65	1	5	2	1	1	1	1	1	1	2	8	8	7	6	5	1	1	1	3
82	1	5	2	13	2	5	6	3	1	2	1	1	1	1	1	1	1	1	2
95	1	5	3	1	1	1	1	1	1	2	8	8	7	6	5	1	1	1	2
105	1	5	3	12	6	3	6	5	1	5	1	1	1	1	1	1	1	1	2
106	1	5	3	12	6	3	6	5	1	5	8	8	7	6	5	1	1	1	2

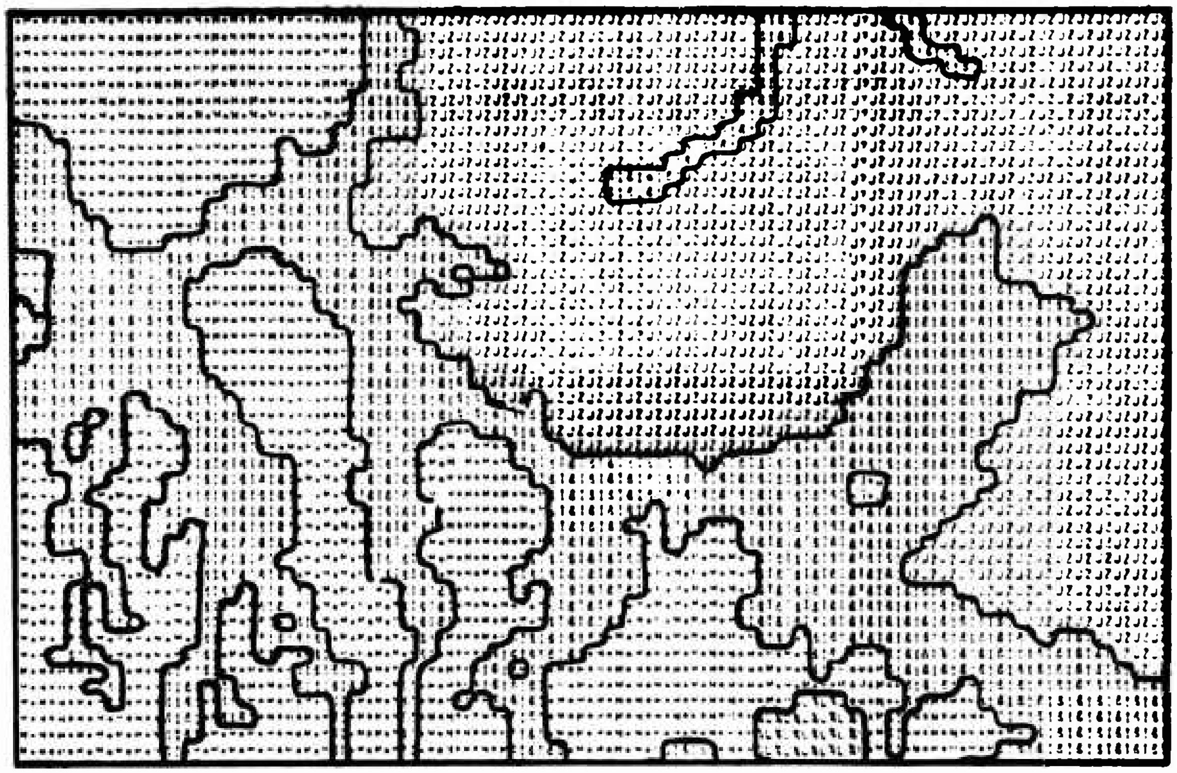
Figure 5. Terrain factor complex map



LEGEND

NUMERIC	DESCRIPTION
110	Village
350	Irregular surface
400	Idle land
403	Idle land with channels <50 meters in width
503	Cultivated land with channels <25 metres in width
780	Gravel or rocky surface with obstacles (lava field)

Figure 6. Manually prepared land use map

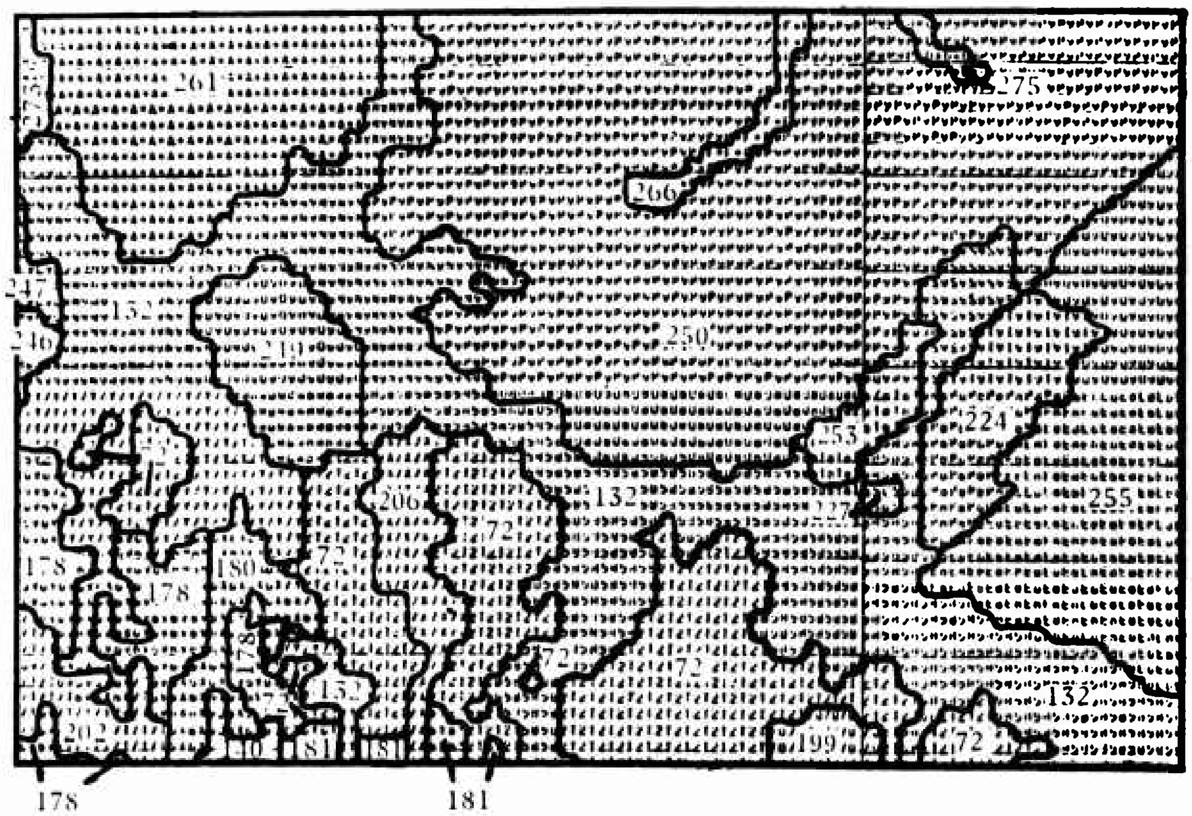


NOTE: Land use boundaries drawn manually.

LEGEND

ALPHANUMERIC	DESCRIPTION
4F	Village
%L	Irregular surface
+J	Idle land
+M	Idle land with channels <50 metres in width
&I	Cultivated land with channels <50 metres in width
JZ and GX	Other land use, gravel or rocky surface with obstacles (lava field)

Figure 7. Land-use maps prepared by computer program



NOTE: Numbers indicate terrain unit numbers.
Terrain unit boundaries drawn manually.

Figure 8. Terrain unit map prepared by computer program

NOTE: Clear areas are no go.
Numbers indicate speed in kilometres per hour.

Figure 9. Illustration of mobility map for a wheeled vehicle prepared by computer program

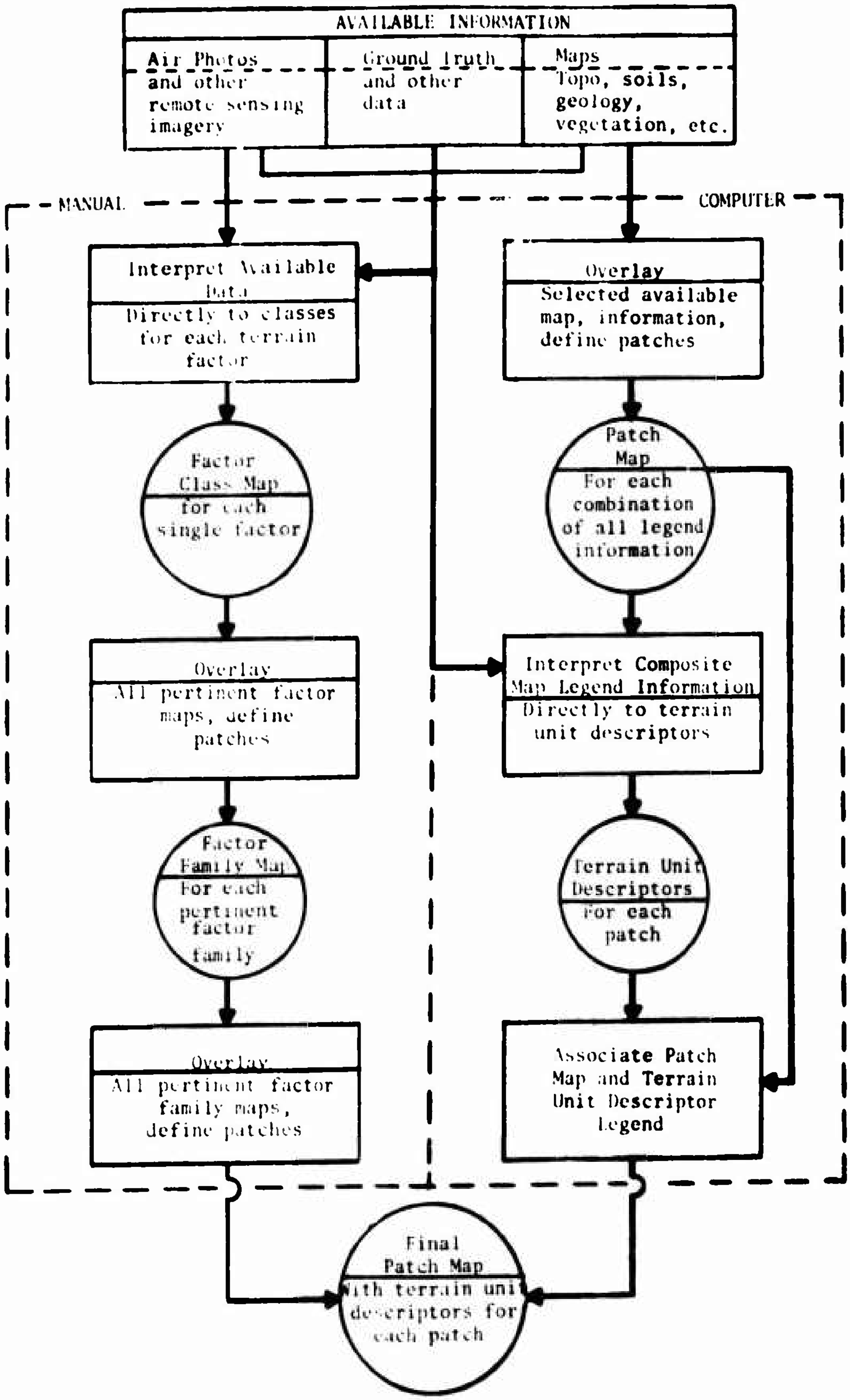


Figure 10. Comparison of procedures used in preparing mobility oriented areal terrain study maps

RIDE DYNAMICS MODULE FOR AMM-75
GROUND MOBILITY MODEL

by

N. R. Murphy, Jr., and R. B. Ahlvin

Background

In December 1969 the U. S. Army Waterways Experiment Station (WES) and the U. S. Army Tank-Automotive Command (TACOM) undertook a unified program to incorporate the existing research and engineering technology of terrain-vehicle-man interactions into a comprehensive computerized simulation of a vehicle moving across a complex terrain. This task was part of a five-year range progressive research plan under the auspices of the U. S. Army Materiel Command (AMC). The plan called for consolidation and synthesis of existing performance prediction methodology and, through systematic research and validation efforts, progression toward a simulation system that would predict performance with a field-demonstrated accuracy sufficient for detailed vehicle design and combat-effectiveness studies.

The first-generation model was completed in July 1971 and was designated the AMC-71 Ground Mobility Model (AMC-71).[1] AMC-71 consists of four basic computational modules: (a) ride dynamics module, (b) areal terrain unit module, (c) linear terrain module, and (d) output module. The ride dynamics module is used to calculate vehicle speed as limited by driver tolerance to shock and vibration when the vehicle is negotiating rough terrains and discrete obstacles. Its primary outputs are two sets of numbers. The first is an array of limiting speed-surface roughness coordinates, and the second is an array of limiting speed-obstacle height coordinates. These arrays represent the ride- and shock-limiting criteria for a specific vehicle and serve as inputs to the areal terrain module.

In the interest of expediency, the AMC-71 ride dynamics module was programmed for four specific vehicles only--two tracked and two wheeled--which were selected at the outset of the program by WES and TACOM representatives as the validation vehicles to be used in a comprehensive program

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to determine the accuracy and utility of the simulation system and assist in making the necessary refinements.

It was understood at the outset of this program that a more general ride dynamics module would be required before the mobility model would be suitable for general use. Therefore, the development of a single computer program that would readily accommodate any type of rigid-framed wheeled or tracked vehicle was included as a part of the proposed five-year plan. This computer program, which is the subject of this paper, has been developed and is referred to as the AMM-75 ride dynamics module.

Description of AMM-75 Ride Dynamics Module

The AMM-75 ride dynamics module is a digital computer program intended primarily for use in determining vehicle speed as limited by shock and vibration. The program is coded for a Honeywell 6000 Series computer for use in either the time-sharing or the batch operational modes and all data are entered in a free-form format. The format for the input data is given in Appendix A. It is restricted to rigid-frame vehicles and two-dimensional (planar) motion, and is capable of handling any type or mix of suspensions that can be represented in a two-dimensional framework. The program requires specific terrain and vehicle factors as inputs, and yields as output the motions at various parts of the vehicle that allow for the determination of the limiting speeds due to shock and vibration in terms of established subjective response limits and specific terrain attributes. Special features of the module are described in the following paragraphs.

Suspensions

The module treats four basic suspension types: (a) independent, which for a two-dimensional model includes also the solid-axle suspension; (b) no unsprung assemblies, such as found on many earthmovers and some military vehicles such as the GOER: (c) walking beams; and (d) bogies. The mass-spring-damper representations of these various suspension types are shown in Figure 1. The module will accommodate any combination of these four suspension types.

The suspension compliance is represented in the form of force-deflection

and force-velocity tables that account for the suspension's elastic and energy dissipation properties, respectively. Frictional (Coulomb) damping may be accounted for through the proper inputs in the force-velocity tables or by including the appropriate hysteresis effects in the force-deflection tables.

Tires and road wheels

Tires and road wheels are modeled as clusters of radial springs (see Figure 2a). The number of springs to suitably describe the tire's compliance is selected by the user. A single coordinate from an experimental (or theoretical) force-deflection relation allows for determination of the spring constant assigned to each spring (see Figure 3). The spring constant is a function of the force-deflection coordinate value and the number of springs representing the wheels. This segmented-wheel concept[2] allows for a more realistic modeling of the effects of tire geometry and distribution of forces in the tire-terrain contact patch.

Tracks

Past experiments have shown that tracks can have a significant influence on the ride dynamics of a vehicle. As a result of a compromise involving model complexity, adequate description of the significant motion, and the time and cost of computer simulations, a tracked model was developed that would be as simple as possible and yet afford suitable simulations of cross-country vibrations.[3] The geometry effects of the road-wheels are represented by radially projecting stiff springs, and the track tension by interconnecting linear springs between adjacent road-wheels. The geometry and track compliance of the forward portion of the track are represented by three variables: the track length measured from beneath the leading road-wheel to the foremost part of the track, the approach angle, and the equivalent spring constant. The track thickness is accounted for by adding an equivalent amount to the radius of the road wheel. A schematic of a tracked vehicle is shown in Figure 2b; that of a half-tracked vehicle in Figure 2c.

Driver response

The user has the option of obtaining either of two types of responses at the driver's location; one includes the driver's motions completely disregarding

the dynamics of the seat, and the other includes the driver's motions and the dynamics of the seat. The latter is obtained by supplying appropriate spring and damping functions for the seat and the weight of the driver.

Absorbed power

Absorbed power is the measure of the rate at which vibrational energy is absorbed by a human and is the quantity currently used to determine human tolerance to vibration when a vehicle is negotiating rough terrain. The digital implementation of absorbed power was derived from two analog circuits[4]. Inputting vertical acceleration to one circuit yields absorbed power in watts; the other circuit averages over a finite time. This finite averaging time prevents saturation of analog components and allows absorbed power to be computed in the field with portable analog instruments during experimental ride tests for both stationary and nonstationary responses. This absorbed power is referred to as "instantaneous absorbed power." The average of instantaneous absorbed power over the total elapsed time is referred to as "average absorbed power." Presently, the tolerance limit is taken as 6-watts absorbed power and the ride limiting speed is that speed at which the driver's average absorbed power reaches a sustained level of 6 watts. Absorbed power is computed only at the driver's position. However, should this quantity be desired at some other location, it can be obtained by designating that location as the driver position. This is accomplished by inputting, for the driver position, the appropriate horizontal distance from the vehicle's center of gravity to the specific location desired.

Program output

The principal output of the program consists of a listing containing an identification block and a summary of all vehicle input data followed by a detailed printout of the displacements, velocities, accelerations, and root mean square (rms) accelerations of the driver and each degree of freedom, along with the driver's instantaneous vertical absorbed power, the cumulative average absorbed power, (averaged over the elapsed time), the distance traveled, the cumulative maximum and minimum of each acceleration, and the corresponding elapsed time. Presently the computer processing time and the execution rate in terms of the computer time required for one record of the problem time is also listed on the printout to provide a basis for estimating

run time and costs. The printout interval is an input variable selected at the discretion of the user and may be any value larger than the time step used in the numerical solution of the differential equations. This time step is an input variable and for optimum efficiency is 0.01 sec for wheeled vehicles and 0.005 sec for tracked vehicles. A separate program is available to plot the desired time histories.

Intitial conditions

The user has the option either to input the initial displacements (the velocities and accelerations must be zero initially) or to let the program calculate them prior to each run. The calculations are based upon an iterative matrix solution, which involves only algebraic computations and consequently converges very rapidly to the proper initial state. The calculation of initial conditions adds no significant increase to run time.

Significant features

The significant features of the module are:

a. Simple data input.

b. Capability of representing any rigid-frame vehicle configuration.

c. Capability of including hysteresis affects.

d. Extended tire/wheel contact.

e. Seat dynamics (optional).

f. Calculation of instantaneous and average absorbed power.

g. Detailed output of all motions, including maximum and minimum accelerations.

h. Accommodation of four types of suspension in any combinations.

i. Accommodation of wheels or tracks, or half-tracks.

j. Capability of representing both viscous and frictional damping.

Basic differences between AMC-71 and AMM-75 ride dynamics modules

Many of the simplifying assumptions and limitations of the AMC-71 ride dynamics module have been eliminated in the development of AMM-75. Basic differences are:

a. The small-angle assumptions of AMC-71 were eliminated in AMM-75.

b. The terrain profiles deflect the wheel-spring segments radially in AMM-75 rather than vertically as in AMC-71.

c. All vehicle characteristics are input as data in AMM-75 rather than requiring a separate program for each vehicle as in AMC-71.

d. An option to include the effects of suspension and tire hysteresis was introduced in AMM-75; it is not in AMC-71.

e. An option to include seat dynamics was added to AMM-75; it is not in AMC-71.

f. AMM-75 accepts two basic formats of input profile data--(1) corresponding stations and elevation coordinates (x,y values), in which case the spacing between profile points does not have to be uniform, or (2) elevations only, in which case they are generated at a constant spacing specified in the input. AMC-71 accepts only elevations spaced at 4-in. intervals.

Current limitations

The module can treat any type of rigid-body configuration. The following are dimension limitations inherent in the current program:

a. Program dimensions and printout format allow for up to only eight wheels.

b. Maximum number of segments per wheel is limited to 50.

c. Maximum number of coordinates (total for all table look-up relations) is limited to 400.

d. The ratio of the vehicle length to the minimum average input profile spacing must be $\leq$ 100.

Assumptions

Generally the assumptions in this program are to provide simplifications. The assumptions of lumped parameters greatly simplifies the analytical effort of modeling the mechanical system. The assumptions are:

a. The main elements are rigid bodies.

b. The external force acts on the vehicle body at a single point.

c. The vehicle has no height.

d. No vehicle element is allowed to deflect in any plane except suspension spring elements, which deflect along their axes.

e. The driver's mass does not influence the motion of the vehicle.

f. Longitudinal forces do not affect the forward motion of the vehicle.

g. The vehicle maintains a constant velocity.

Model Validation

The module's prediction accuracy was of primary concern, particularly the accuracy of the numerical integration routines.[5] Therefore, to obtain a suitable first-order check on the accuracy of the mathematics, the digital module was compared with an equivalent analog module, whose integrators and overall prediction accuracy, particularly the absorbed power routine, had been previously validated.

The vehicle model used in this comparison represented a 4x4 vehicle with characteristics similar to those of an M151 jeep. The suspensions were composed of linear springs and dampers, and each tire was represented by a single linear spring. The vehicle characteristics were identical for both the digital and the analog modules.

Two types of simulations were conducted:

a. A vertical drop test.

b. Two runs at speeds of 5 and 10 mph over a sine wave with a 5-in. amplitude, and a wavelength equal to the base of the vehicle (84 in.).

Results of drop tests

The corresponding motions predicted for the sprung mass center of gravity by the analog and digital modules are shown in Figure 4. Similar agreement between the analog and digital predictions were obtained for the other degrees of freedom.

Results of runs over sine wave

The center of gravity motions resulting from the analog and digital simulations over the sine wave are shown for the 5- and 10 mph runs in Figures 5 and 6, respectively. The close agreement between digital and

analog predictions throughout the successive orders of integration tend to confirm the validity of the numerical integration routines in the digital module and their associated algorithms. However, even though the predicted accelerations for the vehicle's sprung-mass appear almost identical for the two modules, the absorbed power, which is calculated from these accelerations, appears quite different (see Figure 7). The absorbed power calculated for the 5-mph run in Figure 7a by the digital module is a little lower than that calculated by the analog module. On the other hand, the absorbed power for the 10-mph run (Figure 7b) shows the results to be reversed. A more detailed analysis can explain these differences.

Taking first the 5-mph run, a vehicle running at a speed of 5 mph, or 88 in./sec, over a sine wave with a wavelength of 84 in./cycle is being excited at a frequency of about 1.05 Hz. The acceleration traces in Figure 7c reveal the steady-state peak accelerations are 0.85 and 0.95 g for the digital and the analog modules, respectively. Using the formula $P = KA^2_{rms}$[4] for calculating the theoretical absorbed power from sinusoidal waves yields

$$P_d = 0.010233 \times [0.85 \times 32.2 \times 0.707]^2 = 3.82 \text{ watts}$$

$$P_a = 0.010223 \times [0.95 \times 32.2 \times 0.707]^2 = 4.78 \text{ watts}$$

These equations reveal that theoretically a difference of about 10 percent in the acceleration produces about 20 percent difference in absorbed power. For the 10-mph run the vehicle is traveling at 176 in./sec over the sine wave that produces an excitation frequency of about 2.09 Hz. The accelerations in Figure 10c reveal peak accelerations on the order of 2.6 and 2.4 g predicted by the digital and analog modules, respectively. However, in this case, the digital module predicted the higher peak accelerations. Even though at this speed the vehicle models often became separated from the sine wave forcing function causing nonlinear responses and deviations from true sinusoidal responses, the formula $P = KA^2_{rms}$ can still be used to determine a fairly reasonable estimate of the intensity of the theoretical absorbed power:

$$P_d = 0.050971 \times [2.6 \times 32.2 \times 0.707]^2 = 178 \text{ watts}$$

$$P_a = 0.050971 \times [2.4 \times 32.2 \times 0.707]^2 = 152 \text{ watts}$$

Again, small changes in acceleration can produce rather large changes in absorbed power. The absorbed power values predicted by the two modules are compared with the theoretical values in the tabulation below. The agreement between the theoretical and predicted absorbed power values confirms the validity of the absorbed power algorithms used in both models.

Run	Digital Module		Analog Module	
mph	Theoretical	Predicted	Theoretical	Predicted
5	3.82	4.05	4.78	5.10
10	178.0	160.0	152.0	140.0

Although this exercise tends to validate the absorbed power algorithm, it also reveals the sensitivity of absorbed power to small changes in acceleration. This sensitivity should be even more pronounced as the frequency of the acceleration approaches 5 Hz, which is its most sensitive region. This will then be further compounded when dealing with the complex type of wave form occurring in random vibrations that are composed of many frequencies rather than with just a single frequency. Another consideration that can cause complications in multifrequency wave forms is the difference in rates of convergence of absorbed power at different frequencies (see Figures 8 and 9). Consequently, it is evident that much more in-depth study is needed in this area to investigate the sensitivity of absorbed power in both single-frequency and multifrequency wave forms and to explore the possibility of dividing absorbed power into class intervals that are appropriate to the sensitivity at various levels of intensity. This appears to be a necessary step to account for scatter in experimental data that must surely result and before one can expect reasonable comparisons between predictions and experimental results obtained from field tests.

Comparison of Measured and Predicted Ride-Limiting Speeds

Although a detailed analysis of the module's capability to accurately predict cross-country responses was beyond the scope of this paper, a comparison of the measured and predicted ride-limiting speeds as a function of terrain-surface roughness is given for the M151A2 jeep and the M113A1 APC in Figure 10. The ride-limiting speed represents the speed at which a sustained average level of 6 watts absorbed power occurred, and the surface roughness determined from the rms elevations of four profiles representative of the surfaces of the four test courses. The measured and predicted points agree quite well for both vehicles, thus indicating these particular vehicle models appear suitable for predicting ride-limiting speeds at least on these courses. This does not, however, say anything about the accuracy of the module in predicting vehicle motions. The reason for the agreement between the measured and predicted ride-limiting speeds is believed to be due more to the nature of the basic absorbed power versus speed relations than the agreement between predicted and measured vehicle motions. This can better be understood by observing the plot in Figure 11, which illustrates a typical absorbed power versus speed relation. The "saving grace" is the rapid increase in absorbed power with small increases in speed as it approaches the 6-watt ride tolerance level. Large variations in absorbed power in the neighborhood of this 6-watt level produce relatively small variations in speed. There is only about a 2-mph difference between the 6 watt and the 12-watt absorbed power levels. Of course, the slope of the absorbed power-speed curve depends on both the vehicle and the surface over which it is traveling. However, this illustrates how a model could predict ride-limiting speeds rather accurately without accurately predicting the vehicle's motion.

Another reason for the agreement between measured and predicted speeds could be due to the fact that the suspension compliance used in the modules for these vehicle simulations represented the results of carefully measured relations. The lack of proper vehicle relations for inputs to the lumped mass-spring models is believed a major source of error in model predictions. For example, the vertical force-deflection characteristics of a roadwheel

of an M113A1 APC were determined by means of a load cell connected by a cable to the vehicle's road wheel and to a forklift truck. The results are shown in Figure 12. The suspension assemblies in this vehicle were in excellent mechanical condition, yet after sustained exercise of load/unload cycles, the response is characterized by a significant hysteresis loop in which the force in the unload cycle is only about one-half that in the load cycle. The linear force-deflection characteristics of the torsion bar are reflected from strain-gage measurements, but are seen to differ significantly from the true suspension response.

The model prediction would probably be noticeably influenced by the choice of suspension response. Therefore, the actual response including the hysteresis effects was used to describe the suspensions in the simulations with both the M151 and M113 vehicles.

While on the subject of model prediction accuracy, it is worthy to call attention to one other factor that can significantly affect model predictions. This is the accurate modeling of the shock absorber response, which most often is a function of both the position and velocity of the road wheels. This can be visualized by observing the schematic in Figure 13 which illustrates rather clearly how the orientation of the shock absorber changes with the position of the roadwheel. This effect of roadwheel position on the vertical force and velocity components of the shock is currently not accounted for in the AMM-75 ride dynamics module and is, therefore, one of its current inherent weaknesses. However, this deficinecy can be easily corrected and will be addressed in the very near future.

Summary

This paper presents the AMM-75 Ride Dynamics Module, which is a comprehensive, generalized digital computer simulation of the motions of a vehicle that accounts for the interactions of the vehicle, the terrain, and the operator. It is restricted to rigid-frame vehicles and two-demensional (planar) motions but it is capable of handling vehicles--wheeled, tracked or half-tracked--with any combination of four types of suspensions. The module

provides for inclusion of frictional damping and hysteresis effects, seat dynamics, and extended tire contact.

The principal output of the program consists of a listing containing an identification block and a summary of all vehicle input data followed by a detailed printout of the displacements, velocities, accelerations, and root mean square (rms) accelerations of the driver and each degree of freedom, along with the driver's instantaneous vertical absorbed power, the cumulative average abosrbed power, (averaged over the elapsed time), the distance traveled, the cumulative maximum and minimum of each acceleration, and the corresponding elapsed time.

The accuracy of the numerical integration routines were validated by comparison with corresponding predictions of an equivalent analog module. The extreme sensitivity of the primary response criterion--absorbed power--to rather small variations in acceleration and inaccurate representations of suspension compliance were cited as some of the major sources of inaccurate predictions.

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1. U. S. Tank-Automotive Command, "The AMC-71 Mobility Model," Technical Report 11789 (LL 143), Jul 1973, Warren, Mich.

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3. Lessem, A. S. and Murphy, N. R., Jr., "Studies of the Dynamics of Tracked Vehicles," Technical Report M-72-1, Jun 1972, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

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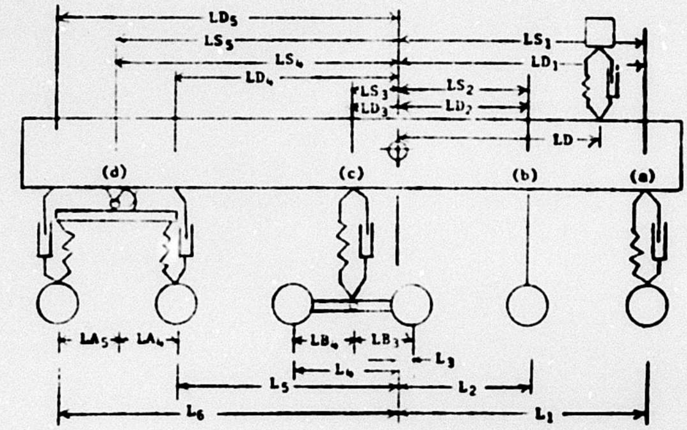
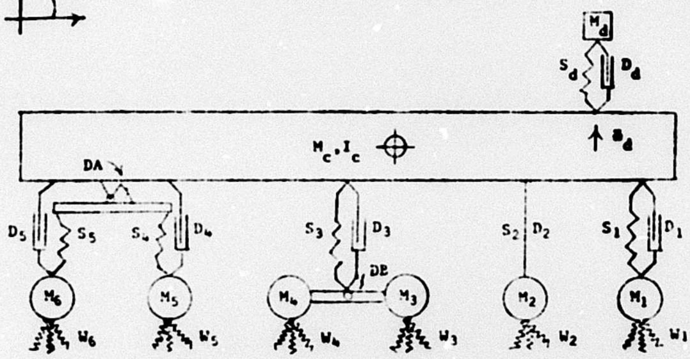
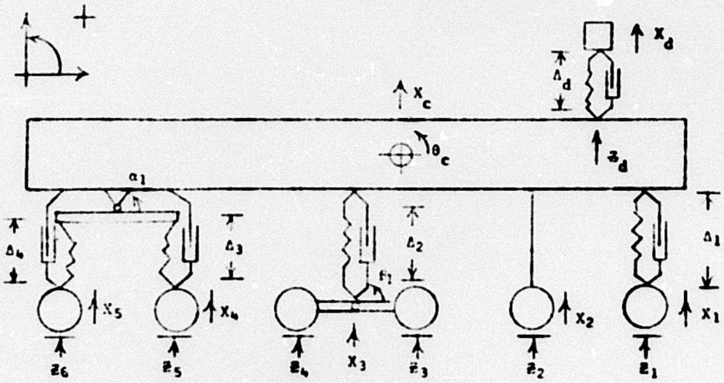
5. Murphy, N. R., Jr., and Ahlvin, R. B., "The AMM-75 Ride Dynamics Module," Technical Report (in preparation), U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.



a. Locations of pertinent dimensions



b. Locations of force producing components

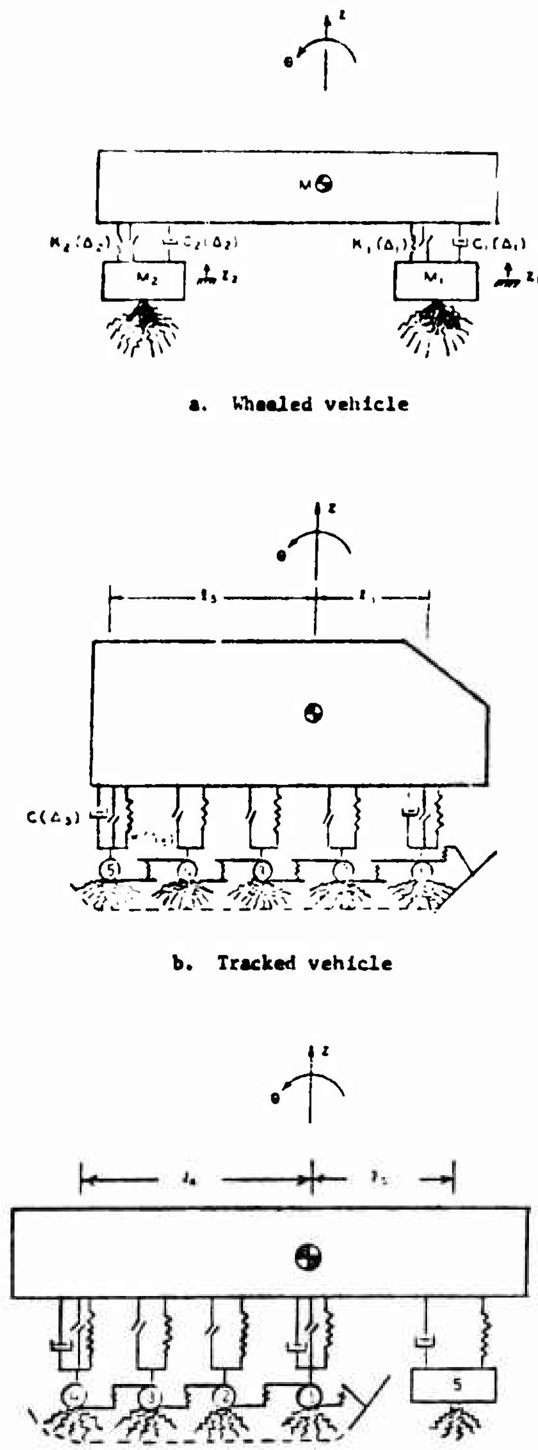


c. Locations of moving elements

NOTE: Suspension types depicted in Figure 1a:

(a) Independent
(b) No unsprung assembly
(c) Walking beam
(d) Bogie

Figure 1. Mass-spring-damper representation of general vehicle model elements

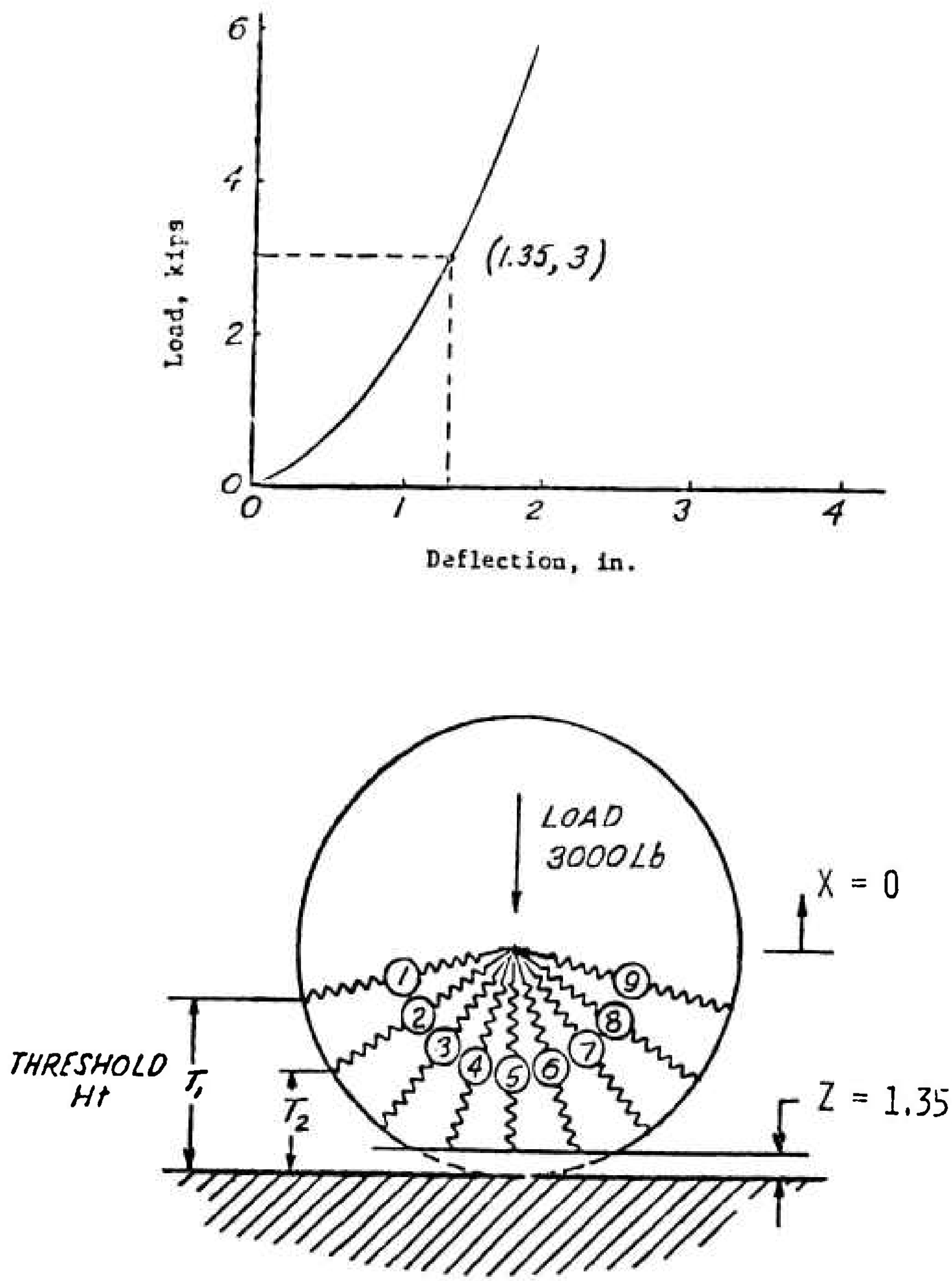


a. Wheeled vehicle

b. Tracked vehicle

c. Half-tracked vehicle

Figure 2. Mass-spring-damper representations of wheeled, tracked, and half-tracked vehicles



$$F = K \sum_{i=1}^{9} \delta_i \cos \phi_i$$

$$3{,}000 = K\,[1.35 \cos 0^\circ + 2\,(1.02 \cos 12.5^\circ)]$$

$$K = 900 \text{ lb/in.}$$

Figure 3. Illustration depicting method of computing spring constant from force-deflection coordinate

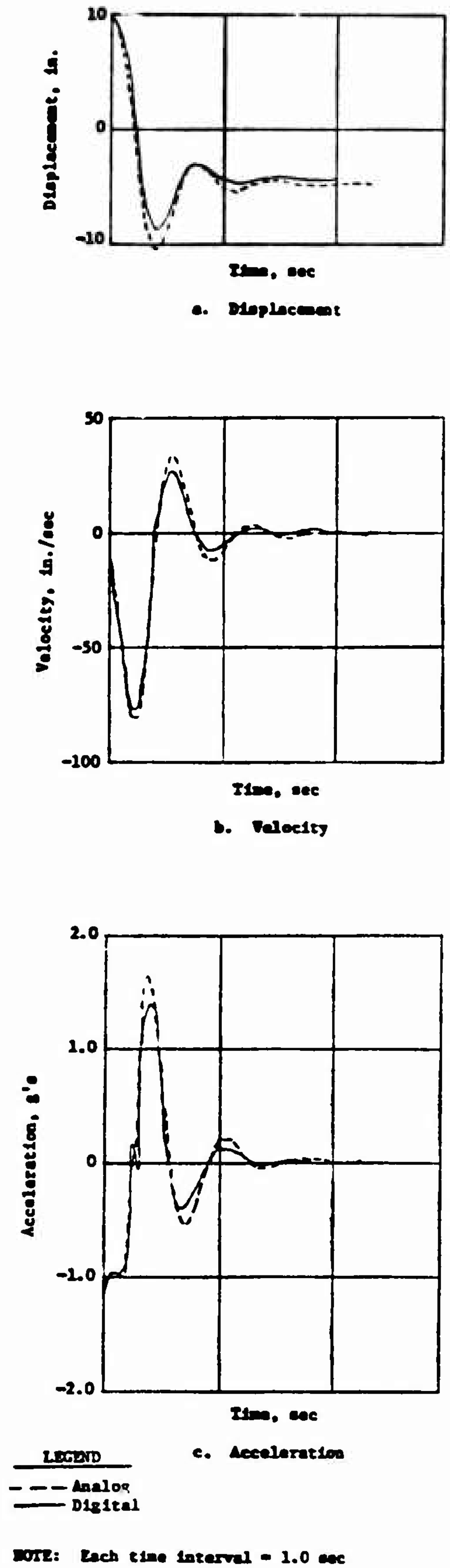
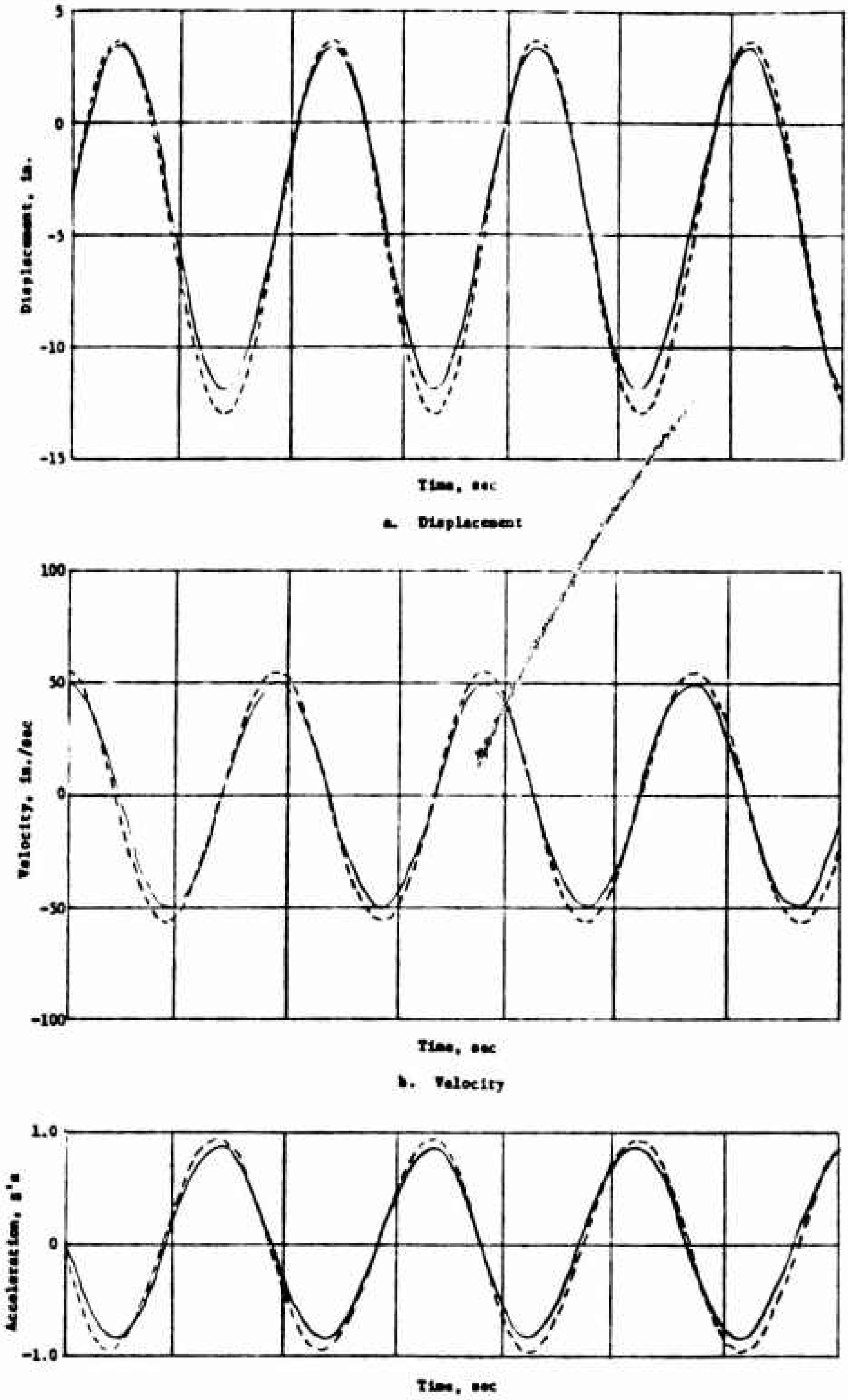


Figure 4. Analog and digital computer simulations of motions at center of gravity of a jeep for a vertical drop test. Initial conditions: sprung mass center of gravity = 10.0 in., pitch = 0.087 radians, front-axle center of gravity = 13.3 in., rear-axle center of gravity = 5.8 in.



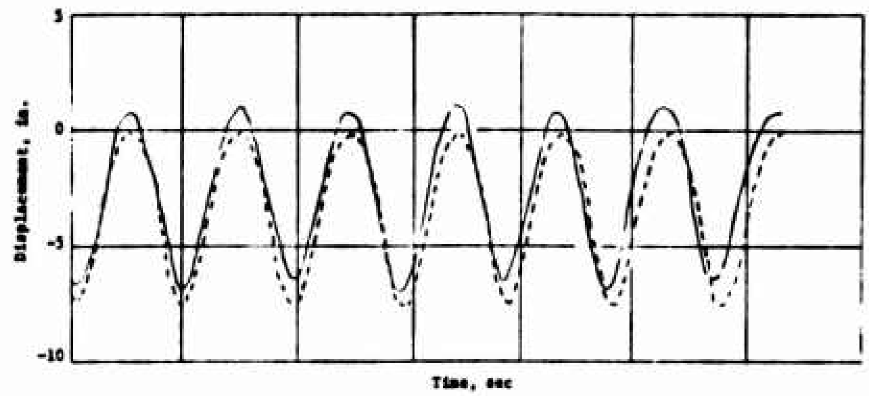
LEGEND

- - - Analog

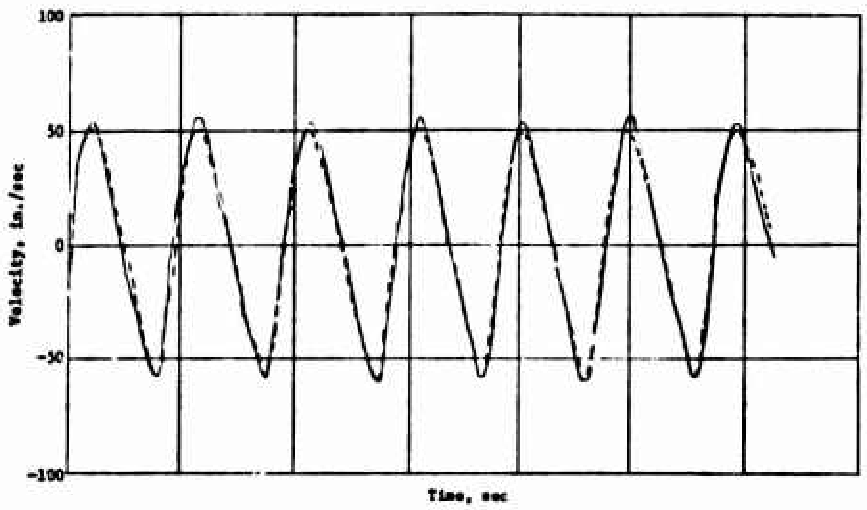
—— Digital

NOTE: Each time interval = 0.5 sec.

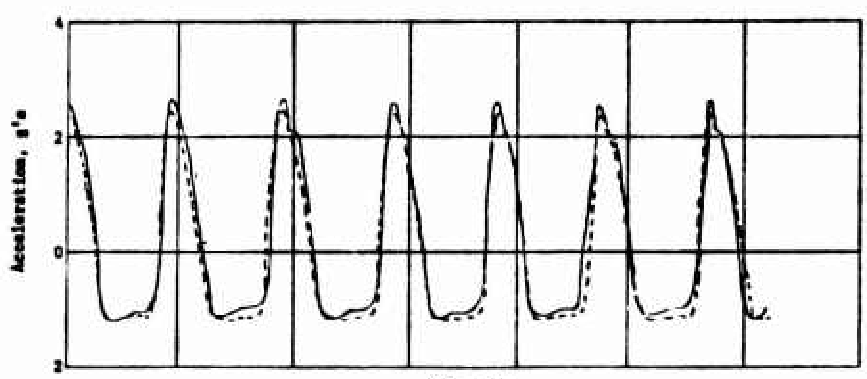
Figure 5. Analog and digital computer simulations of motions at center of gravity of sprung mass of jeep running over a 5-in. sine wave at 5 mph



a. Displacement



b. Velocity



c. Acceleration

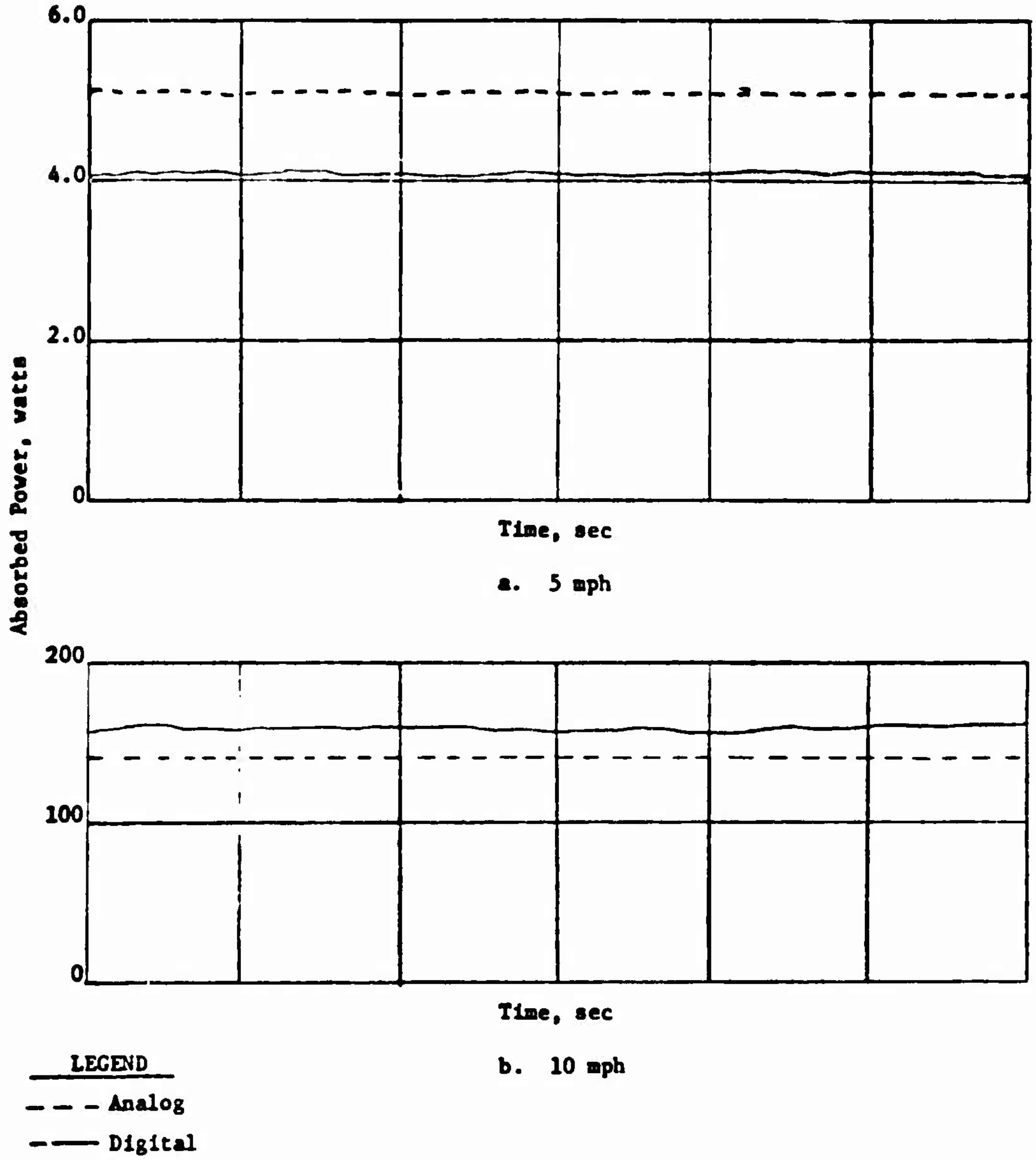
LEGEND

- - - Analog

—— Digital

NOTE: Each time interval = 0.5 sec.

Figure 6 . Analog and digital computer s..ulations of motions at center of gravity of sprung mass of jeep running ov.r a 5-in. sine wave at 10 mph



NOTE: Each time interval = 0.5 sec.

Figure 7 Analog and digital computer simulations of absorbed power of jeep running over a 5-in. sine wave at two speeds

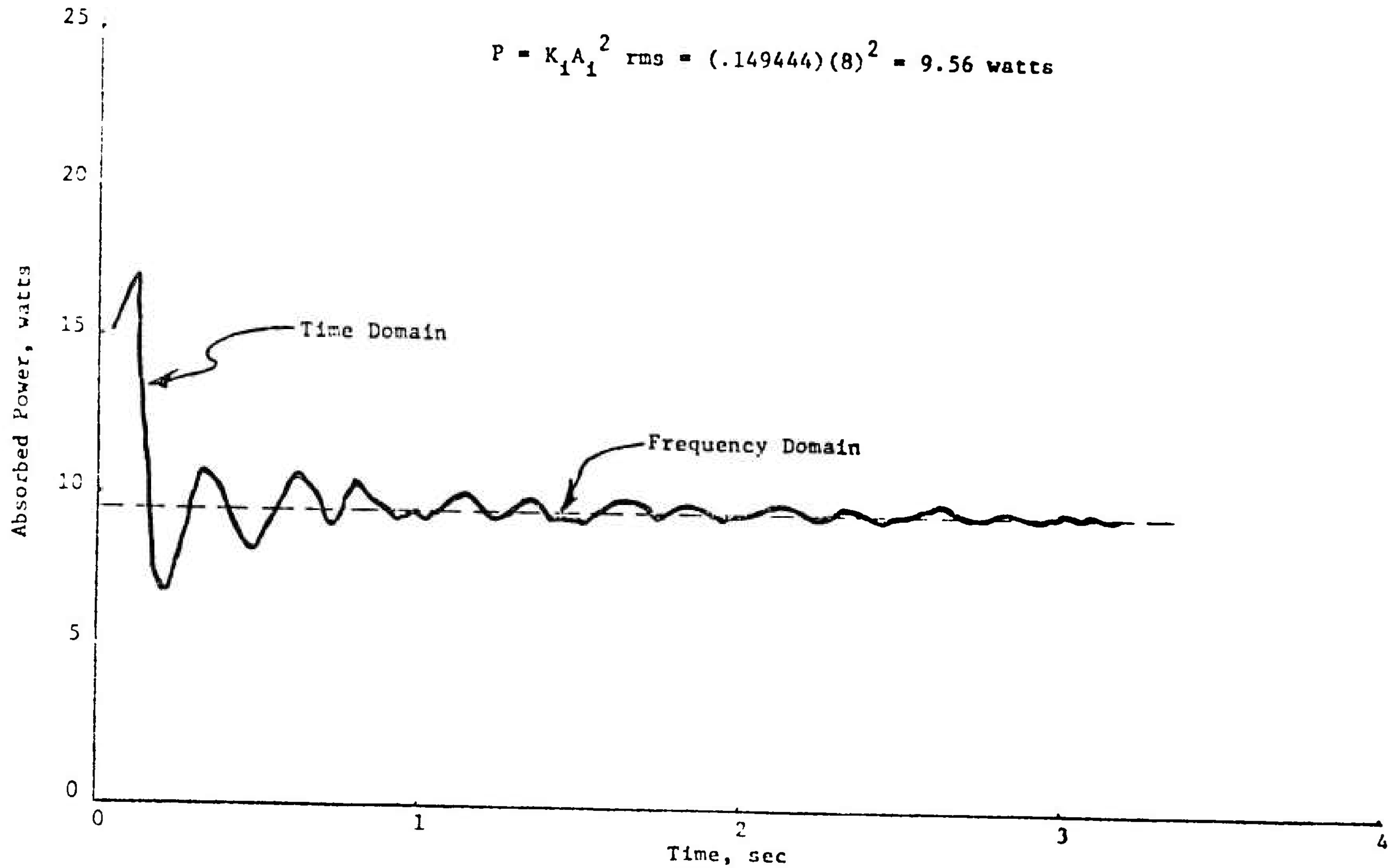


Figure 8. Absorbed power-time history for a sinusoidal input for 8 ft/sec^2 rms at 6 Hz

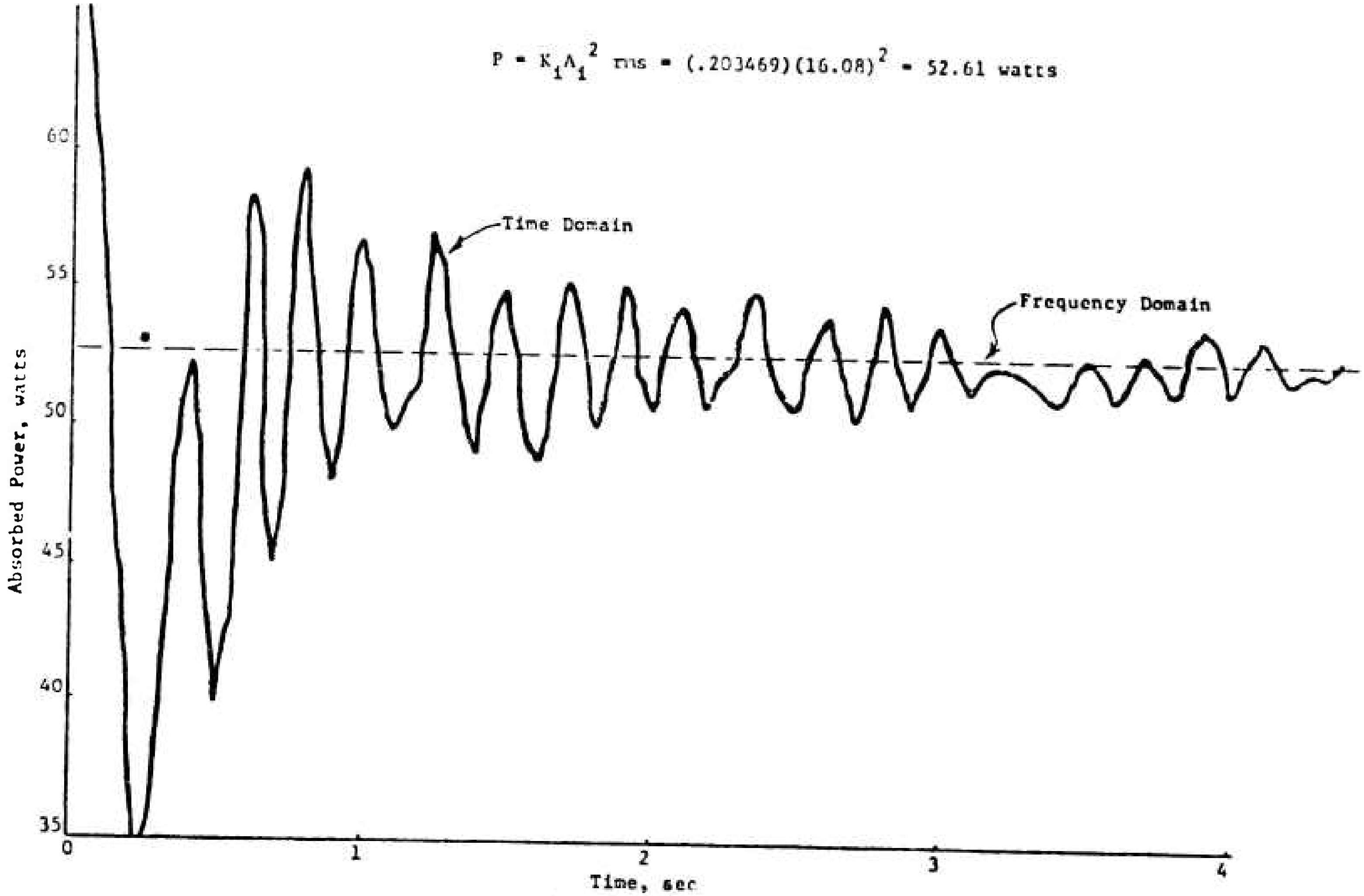


Figure 9. Absorbed power-time history for a sinusoidal input for 16.08 ft/sec^2 rms at 6 Hz.

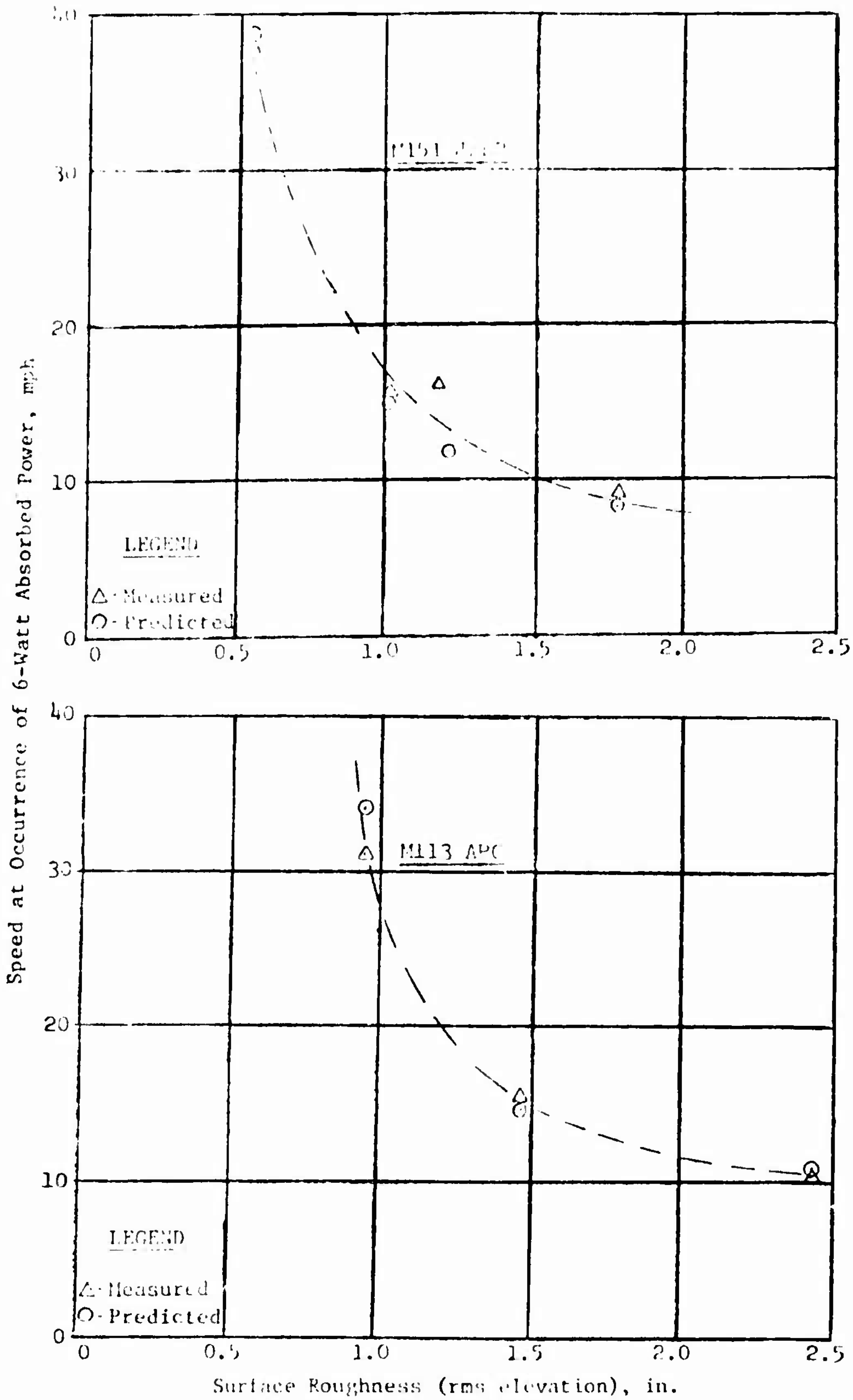


Figure 10. Comparison of measured and predicted ride-limiting speeds for M151 Jeep and M113 APC (AMM-75 Ride Dynamics Module)

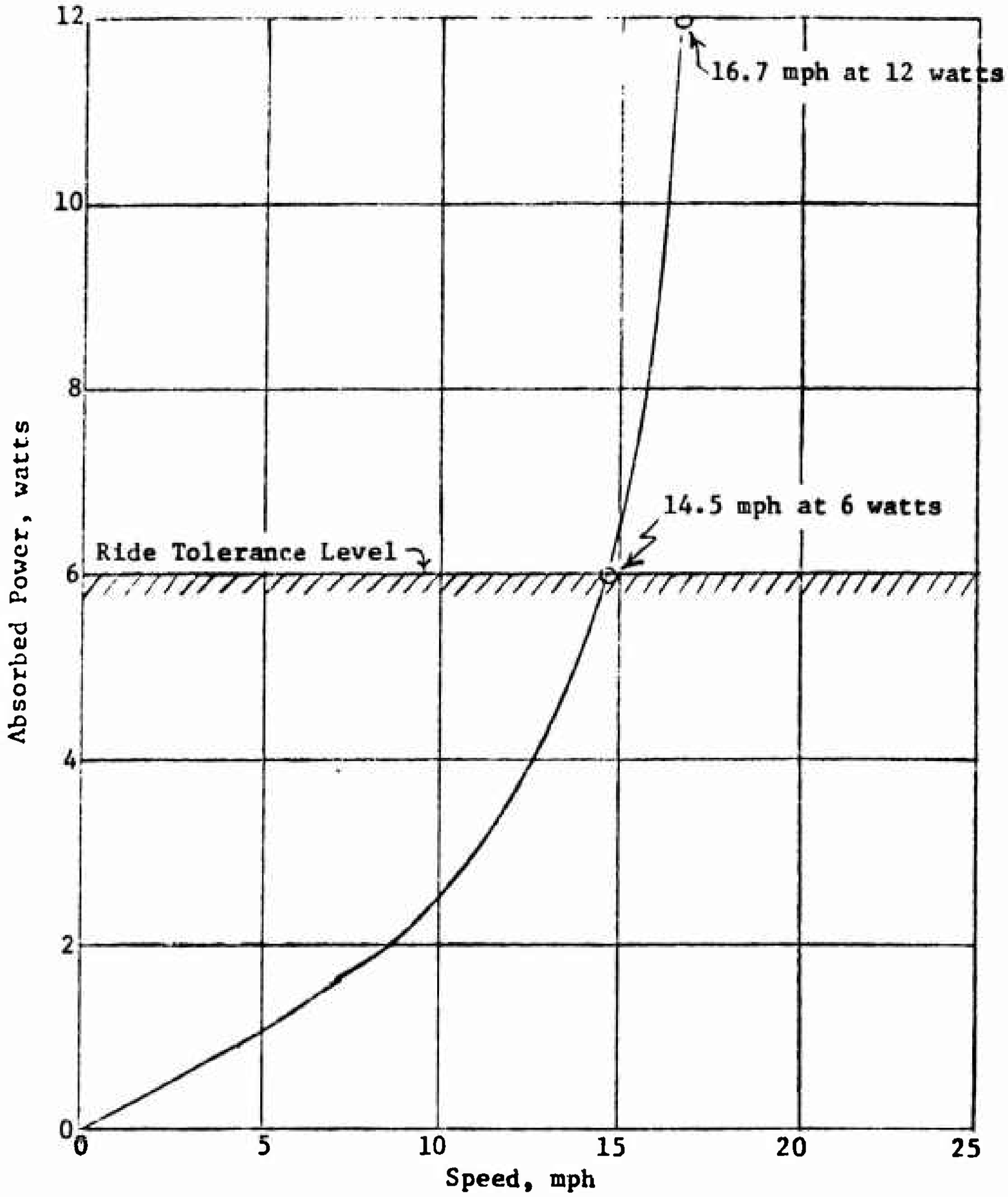


Figure 11. A representative absorbed power versus speed plot illustrating the sensitivity to small changes in speed near the 6-watt level

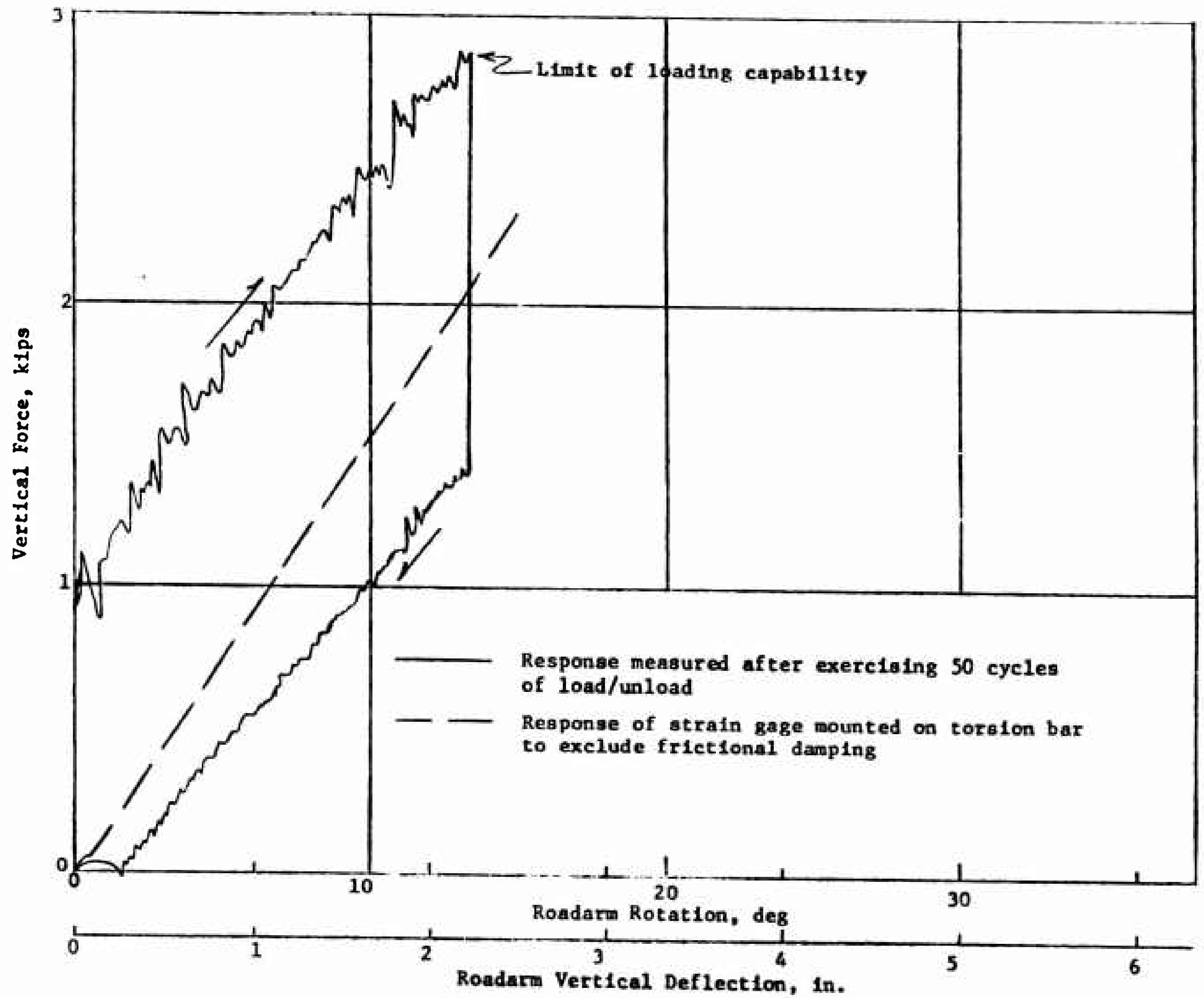


Figure 12 . Measured responses of an M113 APC suspension illustrating hysteresis effects (There was no shock absorber attached to this suspension)

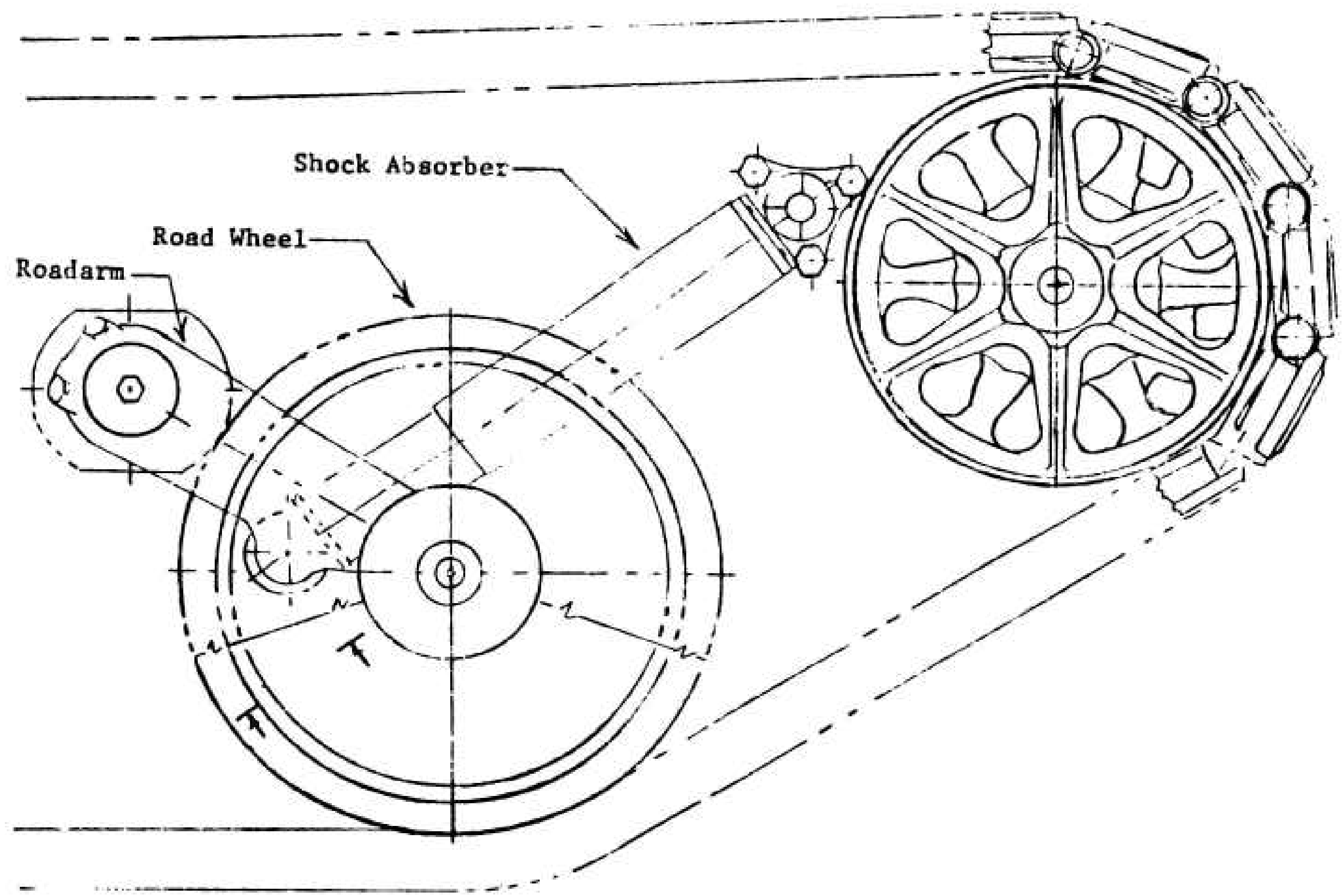


Figure 13. Diagram of shock absorber orientation on a tracked vehicle illustrating how shock orientation varies with the movement of the roadwheel

APPENDIX A: INPUT FORMAT FOR AMM-75 RIDE DYNAMICS PROGRAM

Vehicle Data

The following is a description of the input required for the AMM-75 ride dynamics Module. To distinguish between individual data lines and to establish some sort of a numbering sequence, the data lines have been numbered in a form corresponding to the line number system that could be used in making time-sharing files.

---

100 Vehicle Identification

One line of up to 72 alphanumeric characters for vehicle identification. This line is printed in the program output.

110 Basic Under-Carriage Characteristics

(First Entry) Vehicle type: 1 = wheeled
2 = tracked or mixture of wheels and tracks

(Second Entry) Suspension type: 1 = independent
2 = bogie, walking-beam, or any combination of independent, bogie, and walking-beam.
3 = no unsprung assemblies or any combination of independent and no unsprung assemblies.
4 = any combination of 1, 2, and 3.

(Third Entry) Number of wheels on one side (duals considered as one).

120 Dynamic Properties of Sprung Mass

(First Entry) Gross vehicle weight, lb.

(Second Entry) Pitch inertia of sprung mass about center of gravity, $lb\text{-}sec^2\text{-}in.$

NOTE: The First Entry and Second Entry values are for the whole vehicle and are divided by two within the program. The sprung mass is also computed internally.

(Third Entry) Longitudinal distance of driver from center of gravity, in.

NOTE: Positive if forward of center of gravity, negative if rearward.

(Fourth Entry) Weight of driver, lb.

NOTE: If zero entry then no driver seat dynamics are included. However, motion at driver position is still obtained disregarding seat dynamics.

130 Weight of Unsprung Masses

An entry for the weight of each wheel assembly, lb.

NOTE: For a solid axle suspension, use one-half weight of each axle assembly; for no unsprung assemblies, use zero weight. A wheel assigned a zero weight is considered attached directly to the sprung mass if the suspension type is entered as a 3 or a 4 in line 110.

140 Distances from Center of Gravity

Longitudinal distances of each wheel center from center of gravity, in.

NOTE: Positive if forward of center of gravity; negative if rearward.

150 Segmented Wheel Characteristics

(First Entry) Number of spring segments for each wheel

NOTE: This number must be $\leq$ 50 segments per wheel and is considered the same for each wheel.

(Second Entry) Wheel hysteresis code: 0 = no hysteresis considered

1 = hysteresis considered

(Third Entry) Active angle of segmented wheel, deg.

NOTE: This is an angle > 0 and $\leq 180^{\circ}$, symmetric about vertical center line of the wheel which

designates the boundary of the wheel segments. For a single vertical spring with linear force and deflection characteristics, select an active angle of zero degrees.

160 Wheel Radii

A separate entry for the undeflected radius of each wheel, in. Value must be > 0.

170 Tire Deflection Values

A separate entry for each wheel specifying the deflection in inches from a selected coordinate of a force-deflection relation. This must be a value greater than zero and less than wheel radius.

180 Tire Force Values

A separate entry for each wheel specifying the force from the corresponding coordinate of a force-deflection relation, lb. These values must correspond to the deflection given in line 170.

NOTE: The larger value in the case of a hysteresis loop and must be a value > 0.

190 Tire Force Values

A separate entry for each wheel specifying the force from the corresponding coordinate of a force-deflection relation, lb. Use the smaller value in the case of a hysteresis loop. Omit this entry entirely if tire hysteresis is not considered. The forces in lines 180 and 190 must both correspond to the respective deflections given in line 170.

NOTE: If only independent suspensions are involved, lines 200-230 are omitted.

200 Wheel-Suspension Identification

These entries are to associate the appropriate wheels with the appropriate bogie and walking-beam assemblies. The computer checks for a zero or a non-zero entry for each wheel proceeding from front to rear of vehicle. A zero entry implies the wheel is either an independent suspension or an unsprung assembly. A non-zero entry

implies the wheel is part of either a bogie or walking-beam suspension where a positive non-zero entry denotes a bogie and a negative non-zero entry denotes a walking beam. The value of the integer is the number of the bogie or walking-beam assembly. For example, suppose a vehicle had six wheels on each side. The first two were independently sprung with the remaining four wheels making up two bogie assemblies. The entries would be as follows:

200 0, 0, 1, 1, 2, 2,

If the last four wheels make up a bogie and a walking-beam assembly, respectively, the entries would be as follows:

200 0, 0, 1, 1, -1, -1

210 Length of Bogie or Beam Arms

A separate entry for each wheel specifying the longitudinal distance from the wheel center to the point of attachment to the sprung mass, in.

NOTE: Positive if forward of the attachment point; negative if rearward. A zero entry is required for those wheels which are not part of a bogie or walking beam assembly.

220 Moment of Inertia of Bogie and Beam Assemblies

A separate entry for the moment of inertia of each bogie or beam assembly, lb-sec^2-in. In the preceding examples of the six wheels, there would be two entries and the values would follow in the proper sequence. No zero entries are required for other types of suspensions.

230 Bogie and Beam Rotational Damping

This is a value required for each bogie and beam assembly for the frictional damping resisting rotation. It represents a resisting moment (lb-in.) in the moment equations. The sign is determined by the program and depends on the sense of the velocity. No zero entries are required for other types of suspensions.

NOTE: The following two lines (numbers 240 and 250) are omitted if vehicles are not tracked.

240 Geometry of Forward Edge of Track

(First Entry) The length along the leading portion of the track measured from beneath the leading road wheel to the foremost part of the track, in.

(Second Entry) The approach angle (angle determined by a horizontal line beneath the leading road-wheel and the leading face of the track), deg.

(Third Entry) Equivalent spring constant (lb/in.) determining the track's force-deflection properties measured normal to the leading face of the track.

250 Track Tension

A separate entry for each spring connecting adjacent road-wheels, lb/in.

NOTE: The number of springs is one less than the number of road wheels.

260 Suspension Force-Deflection Relations

. This portion is reserved for suspension spring force-deflection
. tables. A force-deflection table is required for each suspension.
. For the "no unsprung assembly" case, a value of zero in the number
xxx of points entry is the only requirement. The format is as follows: The first line of each table is a single entry specifying the number of force-deflection coordinates. This is followed by as many lines as needed for the coordinate values progressing from the smallest to the largest. The first value represents the deflection in inches, the second value is its corresponding force in pounds each separated by commas. An example for a force-deflection relation defined by four coordinates is as follows:

```
260 4
261 -20, -44330, -10, -1430, 10, 1430, 20, 44330
```

The first coordinate represents a deflection of -20 in. and a corresponding force of -44330 lb.

NOTE: For suspension hysteresis, the table for increasing deflections is followed by a table of force-deflection coordinates for decreasing deflections. This table will

be distinguished from its predecessor by an entry for the number of coordinates which is preceded by a negative sign.

xxx Suspension Force-Velocity Relations

. This portion is reserved for suspension-damping rate tables consist-
. ing of force-velocity coordinates. It requires the same format
. as that of the preceding force-deflection tables. For the case of
yyy no viscous damping, or "no-unsprung assemblies," enter a zero value for the number of coordinates.

NOTE: The combined total number of coordinates for the force-deflection and force-velocity relations must not exceed the program dimension limit of 400.

zzz Initial Conditions

Allows entries for up to 14 initial displacements (initial accelerations and velocities considered zero). The initial displacements are entered in the following sequence: vertical displacement of sprung mass center of gravity, pitch of sprung mass, vertical displacements of suspension assemblies, bogie and beam rotational displacements in the order indicated in line 200, a zero value for horizontal displacement of sprung mass center of gravity, and the vertical displacement of the driver. All linear displacements are entered in inches, all angular displacements in radians.

NOTE: If all initial condition entries are omitted, the program automatically computes the initial conditions prior to each simulation.

Profile Data

Two formats are currently acceptable for inputting profile data: (a) station and elevation coordinates, i.e. x and y data pairs; and (b) elevation only, i.e. only y data implying equal spacing of points. The profile data are stored in a data file in free-form format (one x-y or one y value per line). The first line is for alphanumeric identification. The second line requires only one entry. If this entry is a zero, the data following this line are in terms of station and elevation, respectively: however, if the entry is non-zero then the value is the spacing (in inches) between profile points, and the data following this line are in terms of elevations only. The first line of the profile data file is assumed to be alphanumeric identification (up to 72 characters). All stations and elevations are in inches. If the first elevation is a non-zero value, the data are automatically offset by that value so that the first point is zero. Profile station zero is referenced to the center beneath the first wheel. Allowances for the forward protrusion of the wheel and track must be considered.

Example:

Station and Elevation Data	Elevation Data Only
100 Yuma Course 2	100 Kings-Point Course 6
110 0.	110 4.
120 0., 0.	120 0.
130 1., 0.	130 1.
140 2., 3.	140 -2.
	150 3.

VALIDATION OF THE AMC-71 MOBILITY MODEL

by

B. G. Schreiner and W. E. Willoughby

Abstract

Tests were conducted to validate and evaluate predictions of vehicle performance derived from the AMC-71 mobility model for areal terrain. Predicted vehicle performance was compared to measured performance derived from vehicle tests for a variety of areal terrain conditions to determine prediction accuracy. Test vehicles used in all validation tests included two wheeled vehicles (M151, M35A2 modified) and three tracked vehicles (M113A1, M60 and M48). Priority was given to validating predictions of vehicle performance on traverses and additional tests were conducted to validate performance predictions in terrain units and in terrain conditions required to varify individual relations used in the formulation of submodels.

Analysis of relations involved in the submodel and single terrain unit tests indicate that although some refinement can be made, in general, the power train, measured surface roughness, soil traction, slope, visibility, obstacle spacing, area denied and single tree override relations have an acceptable prediction accuracy. The data also shows marked improvement is needed in the simulated surface roughness, obstacle override, and especially in the maneuver and vegetation relations. Consideration should be given to include relations for tree override when interference occurs, acceleration-deceleration at terrain unit boundaries, and override of deformable obstacles.

Analysis of the traverse tests data showed an overall relative deviation of 30.1 percent or a prediction accuracy of 69.9 percent. Results of the traverse tests indicate that on the average, predicted speeds were higher than measured speeds by +2.9 mph overall. Therefore, study and revision is needed in some areas of the AMC-71 mobility

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model to improve prediction accuracy. Further analysis show that if the simulated surface roughness relations used throughout this study are corrected or are replaced by measured relations and the maneuver relations were corrected, AMC-71 would have an overall speed prediction accuracy of at least 85 percent for the traverse conditions tested.

Introduction

In fiscal year 1971, a unified Army Materiel Command (AMC) ground mobility research program was implemented. Capabilities of the three laboratories responsible for conducting AMC ground mobility research, the U. S. Army Tank-Automotive Command (TACOM), the U. S. Army Engineer Waterways Experiment Station (WES), and the U. S. Army Engineer Cold Regions Research and Engineering Laboratory (CRREL), were geared to achieve common goals. Review of military requirements for vehicle mobility data indicated a common need for an objective analytical procedure for quantitatively assessing off-road vehicle performance. Technology developed through 25 years of Army-sponsored research, along with engineering knowledge of fundamental terrain-vehicle-driver interactions, was incorporated into a first-generation comprehensive computerized analytical ground mobility model called the AMC-71 Mobility Model, or just AMC-71.[1] At the time the model was assembled and became functional, the need for validation was obvious. Thus, a program was initiated in 1971 to validate off-road relations contained in AMC-71 by comparing predicted and measured performances and hopefully to produce results leading to a more refined second-generation model.

Vehicle performance in terrain at any instant in time is a function of vehicle characteristics, terrain features in the area of operation, and driver response. Consequently, the individual system parameters potentially involved must be quantified in engineering terms for calculation of probable vehicle performance as governed by specific terrain-vehicle-driver interactions (Table 1).

Terrain can be described in terms of measurable factors that affect vehicle responses. Each grouping of terrain factors that quantifies the terrain into a specific array of descriptors forms a terrain unit--

Table 1

Terrain, Vehicle, Driver Attributes Characterized in AMC-71 Mobility Model Data Base

Terrain	Vehicle
Surface composition	Geometric characteristics
Type	
Strength	Inertial characteristics
Surface geometry	
Slope	Mechanical characteristics
Discrete obstacles	
Roughness	**Driver**
Vegetation	
Stem size and spacing	Reaction time
Visibility	Recognition distance
	Vertical acceleration limit
	Horizontal acceleration limit

areal, linear, or road--depending on the basic type of terrain described. Although linear and road unit predictions are important aspects of AMC-71, the major part is oriented toward predictions in areal terrain. The large number of vehicle and terrain parameters involved and the complex interactions among them require computation of single terrain feature-vehicle interactions that comprise the submodels that make up the areal terrain module of the off-road model of AMC-71. This paper summarizes the results of validating that module.[2]

Areal Terrain Module

The areal terrain units are characterized by measured specific values (or class intervals) that reflect their surface composition, surface areal geometry, and vegetation. Specific parameters measured for such characterization are listed in Table 2. Specific vehicle characteristics comprise the vehicle data bank for the module.

Maximum safe vehicle speeds in the areal units are calculated by AMC-71 using the specific terrain measurements described above as input to engineering or mathematical relations. These relations are modeled to predict vehicle performance along any given path in the areal terrain, or to accumulate a statistical representation of vehicle performance in the area as a whole, or both. In predicting vehicle speed, terrain units are generally considered homogeneous, i.e., values for each single-factor measurement are considered to be constant, within the same class range, or described by the same probability distribution.

The basic components of the areal terrain module are a series of unique, but interconnected, submodels that contain basic relations designed to model specific vehicle-terrain-driver interactions. These submodels generally use established theoretical or empirical relations, relative to the interactions being modeled, which are coupled to the main body of the model by specific subroutines that either adjust or modify a theoretical vehicle speed or force for the effects of terrain variations on vehicle performance. The submodels are:

Table 2

Content of Terrain Data Bank for Areal Patch
Or Terrain Unit for AMC-71

Terrain Factor		Terrain Factor Family	
		Off Road	
Surface Material			
Type		Surface Composition	Areal Patch
Mass strength		Surface Composition	Areal Patch
Wetness		Surface Composition	Areal Patch
Slope		Surface Areal Geometry	Areal Patch
Obstacle			
Approach angle	Obstacle Geometry	Surface Areal Geometry	Areal Patch
Vertical magnitude	Obstacle Geometry	Surface Areal Geometry	Areal Patch
Length	Obstacle Geometry	Surface Areal Geometry	Areal Patch
Width	Obstacle Geometry	Surface Areal Geometry	Areal Patch
Spacing	Obstacle Geometry	Surface Areal Geometry	Areal Patch
Spacing type	Obstacle Geometry	Surface Areal Geometry	Areal Patch
Surface Roughness		Surface Areal Geometry	Areal Patch
Vegetation			
Stem diameter	Vegetation Structure	Vegetation	Areal Patch
Stem spacing	Vegetation Structure	Vegetation	Areal Patch
Visibility		Vegetation	Areal Patch

a. Power train.

b. Soil and slope.

c. Visibility.

d. Obstacle geometry traction, avoidance, and override.

e. Vegetation override, impact, and avoidance.

f. Maneuvering.

g. Acceleration-deceleration.

Vehicle dynamics (surface roughness and obstacle height versus vehicle impact speed) is a separate module in AMC-71; however, the dynamics module contained therein is so closely related to those in the areal terrain module, it is interfaced with the areal terrain module and is included in this paper.

Terrain and vehicle data files are accessible to the submodels as needed. The logic incorporated into AMC-71 performs an optimal speed analysis to determine the minimum calculated vehicle speed in the described terrain unit as limited by one of the factors comprising the submodels listed above. Following the optimal speed analysis, the predicted minimum speed and the nature of the controlling immobilization (if it occurred) and speed factor are output for each described terrain unit. Immobilization* and speed-limiting factors that control predictions are:

a. Factors governing immobilization:

(1) Surface strength less than vehicle cone index for one pass (factor 1).

(2) Available traction less than surface and slope resistances (factor 2).

(3) Obstacle interference (factor 3).

(4) Available traction less than total resisting forces (factor 4).

b. Speed-limiting factors:

(1) Surface roughness (factor 5).

(2) Combination of surface and slope resistances (factor 6).

---

* See Appendix A for definition of vehicle, soil, and mathematical terms.

(3) Visibility (factor 7).

(4) Maneuvering (factor 8).

(5) Combination of all resisting forces (surface, slope, obstacle, and vegetation) (factor 9).

(6) Acceleration-deceleration between obstacles (factor 10).

Test Program

Tests conducted

Field tests were conducted with two wheeled and three tracked vehicles at five locations where accessibility, variations in terrain, and support were available. Speed tests were conducted over selected single terrain units and over traverses at each location. In addition, the vehicles were tested on specific test lanes to derive data from drawbar-pull, motion-resistance, and slope-climbing tests, and at specific sites to examine obstacle deformation, area denied by obstacles in terrain units, and tree override. Also, data derived from laboratory tests in another test program with two scale-model vehicles, an M35A2 (wheeled) and an M60 (tracked), were analyzed to study traction and obstacle negotiations.

Test sites

To validate the performance predictions from AMC-71 satisfactorily, a variety of sites in which to conduct tests was sought. Test sites were finally selected at Fort Sill, Oklahoma; Yuma Proving Ground, Arizona; Eglin Air Force Base, Florida; Houghton, Michigan; and Fort Knox, Kentucky. These locations are identified in the balance of this report as FS, YPG, EAFB, HTN, and FK, respectively. Detailed terrain data were collected at the time of the tests at each test location.

Vehicle and drivers

The two wheeled vehicles (an M151 1/4-ton truck and a modified M35A2 2-1/2-ton truck) and the three tracked vehicles (an M113A1 armored personnel carrier, an M48 tank, and an M60 tank) used in the field tests

are shown in Figure 1. The modification of the M35A2 truck consisted of replacing the 9.00-20 tires with 11.00-20 tires in single-tandem rear wheels. (When the M35A2 truck is discussed in the balance of this paper, it is to be understood that it is the modified version.) The primary tracked vehicles were to have been the M113A1 and the M60; however, when the M60 was unavailable, the M48 was used as an acceptable alternative vehicle. (The M60 was available at only one of the five test locations.)

The test vehicles were maintained in the best mechanical condition possible to ensure peak vehicle performance. To minimize variations in driving, test personnel (driver and navigator) experienced in cross-country testing and completely familiar with the operation of the test vehicles were used. It is emphasized that for the measured speed to be comparable with the speed predicted with AMC-71, the driver must operate the vehicle at its maximum safe speed.

Validation

Data collected in single-terrain tests or tests on specially selected test courses were used to validate the areal terrain module submodels. Five numerical evaluation parameters were selected to obtain deviations of measured performances from performances predicted with AMC-71.

a. Range of deviation.

b. Mean algebraic deviation.

c. Mean absolute deviation.

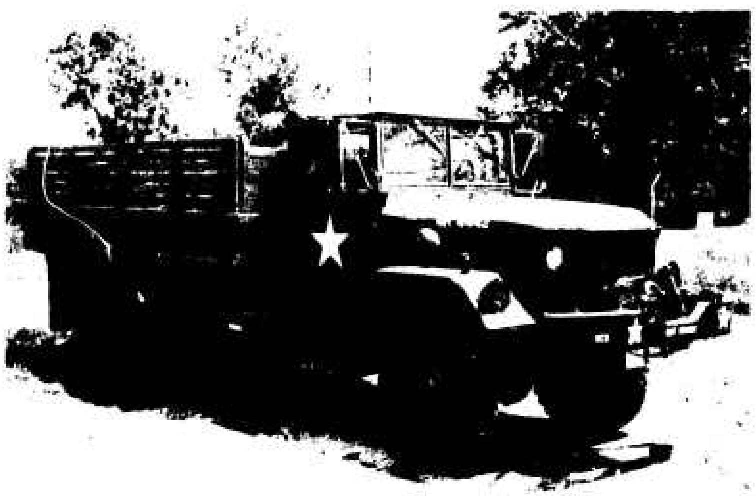
d. Relative deviation.

e. Root mean square deviation.

The submodels previously listed, except for acceleration-deceleration, were considered for detailed validation or evaluation for deficiencies. The vehicle (ride) dynamics module was also examined.

Some comments concerning certain submodels and their relations are appropriate. From the outset of the validation program, weaknesses were

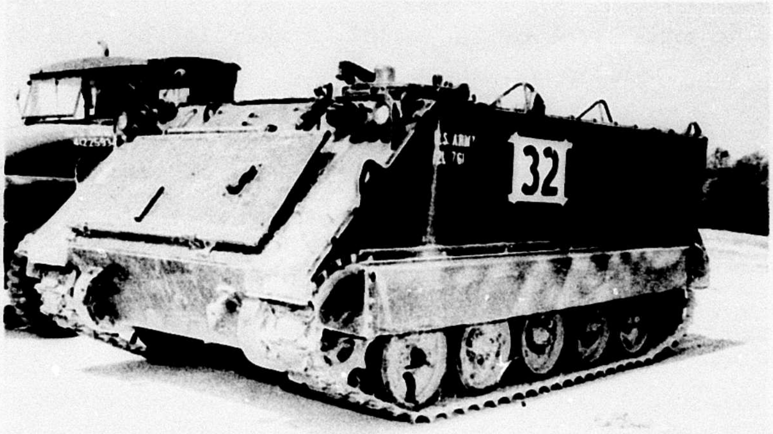
a. M151



b. M35A2 (Modified)

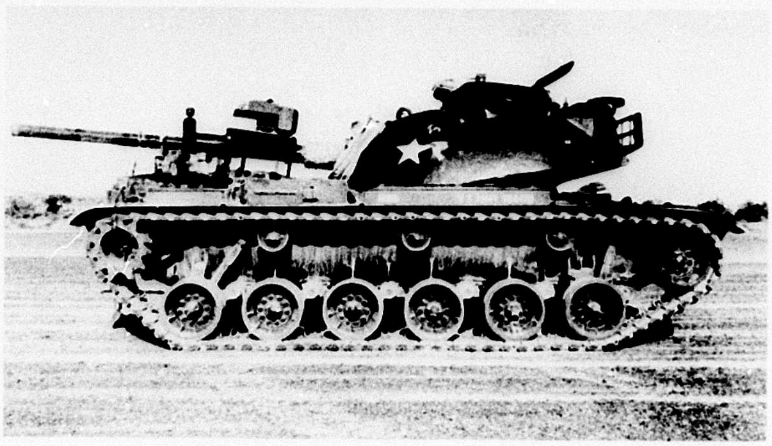
Figure 1. Test Vehicles

(Continued)



c. M113A1

d. M48



e. M60

Figure 1 (Concluded) (2 of 2 sheets)

known to exist in some areas of the model, namely in the ride dynamics module and the acceleration-deceleration submodel. However, ride dynamics is an on-going major research effort designed to obtain a sufficient data base for revisions or restructure of vehicle speed relations as controlled by surface roughness and obstacle heights. Methodology used in formulating AMC-71 did not consider acceleration-deceleration capabilities of vehicles with regard to speed adjustments at the terrain unit boundaries. Only in those terrain units containing significant obstacles does AMC-71 consider these capabilities of a vehicle. In these cases only, a portion of the obstacle submodel (to be discussed later in this paper), which contains an acceleration-deceleration subroutine, will alternately permit acceleration to a point between obstacles (based on the soil strength) then deceleration to contact with the next obstacle. The need for an accurate acceleration-deceleration subroutine to account for terrain unit edge effects became apparent as a result of the traverse testing in this program. Furthermore, certain coupling actions that take place within the model are simply not field testable on an individual basis. For example, measurement of all resisting forces acting on a vehicle at a particular instant of time during a cross-country test is a near impossibility. Consequently, no testing was directed toward measurement of the "combination of resisting forces." Instead, action was directed toward validating or analyzing each force that creates resistance with the understanding that proper modeling of these forces should produce an acceptable summation of the total resistance acting on the vehicle at any increment of time during cross-country operation.

Power Train Submodel

This submodel is designed to accept basic vehicle data input and produce a theoretical tractive force-speed curve for the vehicle. This curve is assumed to represent the best possible performance of the vehicle at zero wheel or track slip and is later adjusted in AMC-71

according to a desired soil strength. If all power losses within the drive train are correctly appraised, the theoretical curve should match the curve developed from tests on hard surfaces. Also, an option is available in AMC-71 to bypass the power train submodel if pavement drawbar pull-speed curves and motion resistance-speed curves are available from reliable tests; these curves may be summed to obtain the tractive force-speed curve.

Using the M60 as an example, Figure 2 shows that the theoretical curve (predicted) derived from the power train submodel is nearly the same as the curve derived from pavement (measured) at Aberdeen Proving Ground.[3] Using an overall efficiency adjustment of 0.81 for the wheeled vehicles and 0.90 for the tracked vehicles, the output of the power train submodel is considered acceptable. More precise agreement could be obtained if all frictional power losses were modeled for each vehicle; however, losses at all points in the power train are seldom measured or published, and consequently, modeling of these losses for a particular vehicle would be difficult. Therefore, generalizations of available data indicate that at the present the method of development of the power train curve is acceptable.

Soil and Slope Submodels

Drawbar-pull (a measure of traction), motion-resistance, and slope-climbing tests were conducted during the field program. The predicted vehicle performances for these tests are based on the traction force relations of the AMC-71 soil and slope submodels.

Drawbar-pull tests

Drawbar pull divided by vehicle weight (drawbar-pull coefficient, D/W) versus wheel or track slip for each test was plotted, and curves of best visual fit were drawn through the data points. Results of previous studies have indicated that the optimum drawbar pull for most vehicles consistently occurs at about 20 percent wheel or track slip (40 percent slip for tracked vehicles on coarse-grained soil). Therefore, the

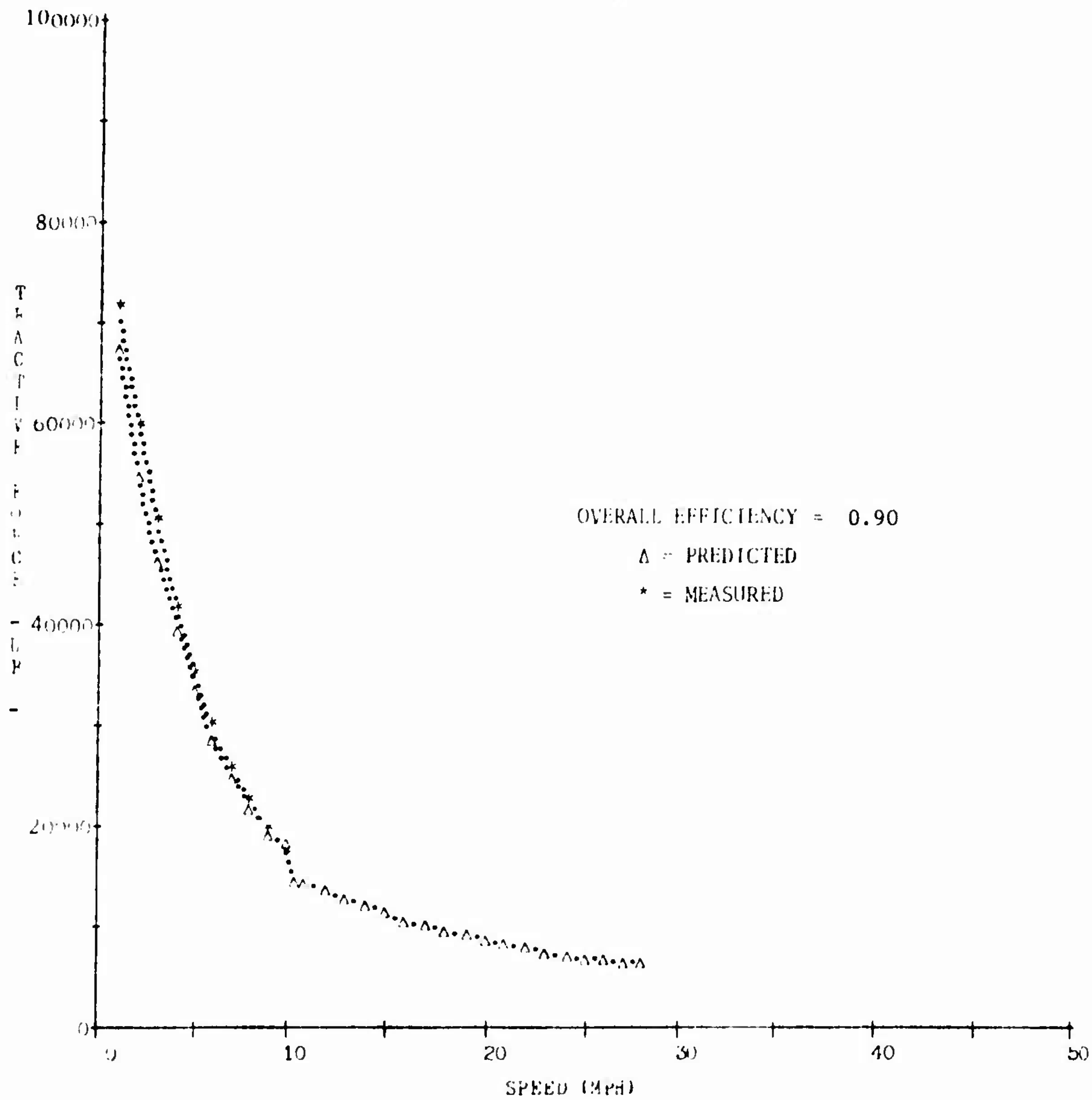


Figure 2. Tractive Force vs Speed For the M60

5-14

drawbar-pull coefficient at 20 percent slip (40 percent slip for tracked vehicles on coarse-grained soil), which can be predicted with the AMC-71 soil submodel, has been found to be a meaningful parameter for comparing vehicle performance. Analysis of these tests, by vehicle, using the five evaluation parameters previously listed indicate the following:

		Numerical Evaluation Parameters				
No. of Tests	Vehicle	Range of Deviation D/W	Mean Algebraic Deviation D/W	Mean Absolute Deviation D/W	Relative Deviation %	Root Mean Square Deviation D/W
		Fine-Grained Soil, FS				
7	M151	-0.04 to 0.11	0.02	0.04	11	0.05
6	M35A2	0 to 0.08	0.03	0.03	7	0.04
8	M113A1	-0.12 to 0.01	-0.02	0.02	4	0.04
7	M48	-0.04 to 0.05	0.01	0.03	6	0.03
		Coarse-Grained Soil, YPG and EAFB				
4	M151	-0.03 to 0.07	0.02	0.05	13	0.05
7	M35A2	-0.16 to 0.09	-0.04	0.09	25	0.10
8	M113A1	-0.09 to 0.15	0.03	0.08	16	0.09
2	M60	-0.10 to -0.01	-0.06	0.06	10	0.07

The weighted average* relative deviation for all vehicles in the fine-grained soil tests was 7 percent, or 13 percent less than the maximum deviation of 20 percent considered acceptable for prediction

* Weighted average of deviations $= \dfrac{\sum \text{No. of Tests x Relative Absolute Deviation}}{\text{Total No. of Tests}}$

accuracy for AMC-71. Consequently, although the number of tests is limited, the drawbar-pull data indicate good prediction accuracy for fine-grained soil. The weighted average relative deviation for all vehicles in the coarse-grained soil tests was 17.9 percent, indicating acceptable prediction accuracy. The greatest relative deviation for the test vehicles occurred in tests with the M35A2, which was 5 percent above the acceptable 20 percent prediction error. The coarse-grained soil relations in AMC-71 were primarily developed from tests on clean sands (SP according to the Unified Soil Classification System, USCS); whereas most of the validation tests, although on coarse-grained soil, were on silty sands (SM). The difference in the two soils, both coarse-grained, undoubtedly affected the predictions to some extent. For this reason greater deviations are to be expected in coarse-grained soil results than in the fine-grained soil results. These data then indicate that some refinement is needed in the coarse-grained soil relations to account for different types of coarse-grained soils.

Motion-resistance tests

Motion resistance of each vehicle was measured in each terrain unit in conjunction with the drawbar-pull tests. In addition, six motion-resistance tests were conducted in a vegetation override area at EAFB. Motion-resistance coefficients (motion resistance divided by vehicle weight MR/W) were computed. Analyses of these tests, by vehicle, using the five evaluation parameters, show the following:

No. of Tests	Vehicle	Range of Deviation MR/W	Mean Algebraic Deviation MR/W	Mean Absolute Deviation MR/W	Relative Deviation %	Root Mean Square Deviation MR/W
		Numerical Evaluation Parameters				
			Fine-Grained Soil, FS			
7	M151	-0.05 to 0	-0.01	0.01	7	0.02
6	M35A2	-0.01 to 0	-0.003	0.003	0.3	0
8	M113	-0.02 to 0.01	-0.004	0.009	5	0.01
7	M48A3	-0.05 to 0.01	-0.007	0.01	5	0.02
			Coarse-Grained Soil, YPG and EAFB			
9	M151	-0.03 to 0.04	0	0.02	26	0.03
8	M35A2	-0.02 to 0.03	0.008	0.13	18	0.02
8	M113A1	0 to 0.04	0.02	0.02	30	0.03
2	M60	0.03 to 0.04	0.04	0.04	54	0.04

The weighted average relative deviation for all vehicles from the fine-grained soil tests was 4 percent. Although, the number of tests is limited, the MR/W data indicate good correlation between measured and predicted values for fine-grained soil. The weighted average relative deviation for all vehicles from the coarse-grained soil tests was 32 percent, or 12 percent over the acceptable prediction error. A greater deviation is to be expected in coarse-grained soil results than in the fine-grained soil results for reasons previously discussed. Results again indicate that refinement is needed in the coarse-grained soil relations.

Slope-climbing tests

Slope-climbing tests in terms of go or no-go were conducted at YPG on coarse-grained soil. A summary of test results is shown in the following tabulation.

Vehicle	Total	Number of Tests: Measured Go	Measured No-Go	Predicted Go, Measured No-Go	Predicted No-Go Measured Go
M151	30	13	17	0	4
M35A2 (mod)	28	11	17	5	2
M113A1	26	20	6	6	0
M60	6	2	4	4	0

The 30 tests with the M151 were conducted on gravel and sand slopes with average tire inflation pressures of 7.5, 15, 30, and 40 psi. The slopes ranged between 8.5 and 43.0 percent (with a cone index range between 17 and 527). The 28 tests with the M35A2 were conducted on gravel and sand slopes with average tire inflation pressures of 10, 15, and 30 psi. The slopes ranged between 8.5 and 43.0 percent, with a range in soil strengths. A detailed analysis of the test results indicates generally good agreement between predicted and measured go-no go performance for the wheeled vehicles, except for the M35A2 on slopes where soil strength was low; these predictions appear slightly optimistic. Seven gravel slopes on which the M113A1 was tested ranged from 40.9 to 61.8 percent. The predicted maximum slope negotiable for the M113A1 was 69 percent whereas the measured data indicate that the maximum slope negotiable was approximately 58 percent, giving a 19 percent deviation. Nineteen sand slopes tested ranged from 12.1 to 49.7 percent (with a cone index range between 17 and 461). The maximum slope negotiable was predicted to be 69 percent; the measured data indicated a maximum negotiable slope of 40 percent, producing a 73 percent deviation. Four gravel slopes tested with the M60A1 ranged from 46.1 to 52.8 percent. The data show that maximum slope negotiable was predicted as 69 percent; the measured was 47 percent, producing a 47 percent deviation.

Only two sand slopes were tested--a go test on a slope of 32.3 percent, and a no-go test on a slope of 33.5 percent. The maximum slope negotiable was predicted at 69 percent; the measured was 33 percent, producing a 109 percent deviation. For the tracked vehicles, the results of the field tests indicate poor correlations between predicted and measured slope-climbing results. The correlations probably would be improved by including a parameter to better account for strength changes in coarse-grained soil in the tracked vehicle relations in AMC-71. Therefore, study and revision of these relations are needed.

Visibility Submodel

In AMC-71 the visibility submodel considers the effect on the driver of obscuration by vegetation and, consequently, the effect on vehicle speed. The submodel is currently based on the premise that in any terrain situation there is a practical limit imposed upon the speed a vehicle may safely achieve: The vehicle should at no time exceed that speed at which the driver can recognize a menacing obstacle and be able to stop his vehicle in time to avoid hitting it. The factors considered in this submodel are velocity, driver reaction time, braking coefficient, stopping distance, and recognition distance. Predicted vehicle speed relies heavily upon and, for the most part, is limited by recognition distance. Driver reaction time and braking coefficient used in the visibility submodel were originally developed from actual test data and were found to be essentially unchanged in these preliminary validation tests.

Detailed investigation of the test data showed that in only 33 of the 487 terrain unit tests considered, or 7 percent of the total, did the test driver exceed the maximum speed predicted by the visibility submodel. However, in these 33 tests measured speed was generally low (less than 20 mph in 22 of the 33), and except for one test, all speeds were within 5 mph of predicted speeds. Further, the driver did not hit any dangerous obstacles in these tests, but if he had, theoretically he

should have been able to slow the vehicle to at least 5 mph before it hit; at this speed the driver probably would not have been injured nor the vehicle damaged to the point of immobilization. Considering that measured vehicle speed controlled by visibility is purely a driver's decision, these test data indicate that in AMC-71 the method used to determine recognition distance for the terrain and the visibility relation predicts a practical maximum speed that compares reasonably well with the maximum speed an expert cross-country driver would actually be willing to travel.

Since natural potholes seldom occur, the recognition distance and vehicle speed prediction with AMC-71 at present do not account for the pothole type of terrain feature in the visibility submodel. Potholes, large and deep enough to immobilize a vehicle or to injure the driver if they are hit, are not often present in terrains unless man puts them there. However, in terrains where menacing potholes are known to exist, predicted and actual speeds are presently and should be kept to walking speed.

Obstacle Submodels

In AMC-71 the obstacle and vegetation submodels are coupled together. Forces, speeds, and other pertinent data are calculated in each submodel but stored for use as required by the coupling program, which examines the various obstacle-vegetation-slope combinations possible for a given terrain input. It is assumed in the submodel relation that all of the obstacles are rigid. Immobilization is predicted if there is any interference at any time during the complete passage of the vehicle over an obstacle. The normal output from the obstacle submodel is either an interference, caused by obstacle-vehicle interaction or insufficient traction, or a speed at which the vehicle can cross the obstacle. If interference occurs, vehicle speed is set equal to zero and a no-go situation is predicted.

Scale-model vehicle tests
over rigid obstacles

Tests were conducted with a scale-model M60 and a scale-model M35A2 over a range of convex and concave obstacles having a range of surface traction coefficients between 0.12 and 0.55. Test results on a go-no go basis are summarized in the following tabulation.

Vehicle	Total Number of Tests	Number of Tests: Measured Go	Measured No-Go	Predicted Go Measured, No-Go	Predicted No-Go, Measured Go
M35A2	133	62	71	29	0
M60	66	42	24	1	16

Analysis of test results with the M35A2 indicate that geometric configuration and shape, along with traction, are important in determining go-no go performance with wheeled vehicles on obstacles where the obstacle approach angle is between 110 and 250 degrees. Results show that in 29 of the 133 tests conducted, go performance was predicted and no-go was actually measured. The reason for the no-go in 13 tests was vehicle hang-up, and in the other 16 tests, the reason for no-go was lack of traction. These results indicate that in some cases predictions of vehicle performance are too optimistic.

Results of scale-model rigid obstacle tests with the M60 indicate very little effect of obstacle geometry on vehicle performance. No hang-ups occurred while the vehicle was crossing these obstacles. All no-go conditions, predicted and measured, were caused by insufficient traction. Based on the large number of obstacle configurations used in these tests, it appears from the results that the problem of obstacle interference for tracked vehicles is negligible.

Field obstacle tests,
deformable obstacles

Obstacle-crossing tests were conducted at YPG and FK in terrain where natural erosional processes had created dry streambeds with banks that had different step heights. Tests were conducted at YPG with the

M151 and at FK with the M113A1 to obtain data on concave obstacles in which the vehicle deformed the sides of the obstacles during vehicle crossings.

Results predicted with AMC-71 and measured results of obstacle tests at YPG and FK are as follows:

Vehicle	Total Number of Tests	Number of Tests: Measured Go	Measured No-Go	Predicted Go, Measured No-Go	Predicted No-Go, Measured Go
M151	11	6	5	0	6
M113A1	6	1	5	0	4

In the field tests with the M151 and M113A1 that produced measured go results, but no-go was predicted, go results were generally the result of deformation of the obstacle and deflection of the vehicle suspension system. Since obstacle deformation is not considered in AMC-71, the disagreement between measured and predicted results in these tests was to be expected. Nine predicted no-go's that were measured go's also occurred in terrain units at FS and YPG with tracked vehicles. These no-go's again point to the conservatism of the obstacle submodel predictions for tracked vehicles. In summary, the obstacle override submodel generally overstates the hang-up problem relative to tracked vehicles negotiating obstacles. More traction checks appear necessary for adequate prediction of vehicle performance, and more tests are required to develop and improve the interference relations for wheeled vehicles in the obstacle submodel.

Area denied by obstacles

Important to AMC-71 predictions is the percentage of area of a terrain denied to a vehicle by obstacles. The basic equations in AMC-71 were derived from tests that showed that percentages greater than 50 percent usually produced a no-go condition (more than half the area was not usable); whereas percentages less than 10 percent seemed to have little or no effect on vehicle performance.

Tests were conducted with the M151, the M35A2, and the M113A1. The predicted minimum obstacle spacings required for the vehicles to circumvent all obstacles of a terrain unit were: for the M151, 7.8 ft; for the M35A2, 12.0 ft; and for the M113A1, 13.1 ft. Results of some of the tests are as follows:

Mean Obstacle Spacing in Terrain Units ft	Area Denied, %			Measured Speed, mph		
	M151	M35A2	M113A1	M151	M35A2	M113A1
3.5	217.2	477.2	563.4	No-go	No-go	No-go
7.3	60.6	134.3	159.0	No-go	No-go	No-go
13.7	19.1	41.4	48.3	19.2	8.0	9.8
15.2	15.6	33.7	39.7	*	12.4	16.8
8.8	41.3	92.9	110.3	2.3 (No-go**)	No-go	No-go

* M151 was unavailable for testing because of mechanical failure.
** M151 completed initial run at 2.3 mph by constantly maneuvering or reversing direction. Three more attempts to complete a test using different paths were unsuccessful.

The results of the five tests shown above seem to bear out the 50 percent and 10 percent limits. For example, the M151 was unable to complete a test in which 60.6 percent of the area was denied, but was able to just complete a test in which 41.3 percent of the area was denied. Also, results show the M151 completed a test in an area denied of 19.1 percent at 19.2 mph, but could not negotiate the terrain unit at 25 mph because this speed was too fast to allow maneuvering. It appears likely that an area denied of less than 10 percent would not affect vehicle speed. With some extrapolation, the general trend of the results of the M35A2 and M113A1 tests would indicate similar agreement.

Analysis of all test results indicate that the present relations in AMC-71, provide acceptable results for consideration of the effects of area denied on vehicle performance. Further analysis of these effects on vehicle performance will be discussed under the vegetation and maneuvering submodels, which follow.

Vegetation Submodel

The vegetation submodel contains relations associated with optimization of forces or speeds from other submodels. Tests were conducted to validate significant relations of peak tree-override forces and quantity of work required to override single and multiple trees, and the maximum single stem diameter each vehicle was capable of overriding.

Tree-override tests

Test results indicate that although the predicted and measured values shown for the single-tree tests establish no definite pattern relative to each other when plotted on 1:1 plots as shown in the example in Figure 3, the data scatter is no greater than the scatter of data used to develop the original relations. The original results and these data indicate that the growth of individual trees is a function of their environment and, consequently, individual trees of the same size and species at the same geographic location and in the same soil type do not necessarily exhibit the same test behavior. Nevertheless, the relations now used generally produce predictions that are considered adequate for all sizes and species of trees pertinent to vehicle operation. However, results of further tests and study may indicate refinement can be made to the tree-override relations to produce more accurate predictions.

AMC-71 relations governing vegetation override and maneuvering assume the vehicle driver would override trees up to the maximum stem size that the vehicle was capable of overriding, after which he would begin to maneuver around those trees larger than the maximum. To determine the validity of this assumption, all trees overridden in each terrain unit were recorded for each vehicle test. Although the quantity of trees overridden decreased as diameter increased, in none of these tests did the vehicle override a tree equal to the maximum diameter negotiable. In most tests the driver usually maneuvered around trees larger than 5 to 6 in. in diameter with the larger vehicles and trees more than 3 in. in diameter with the M151. As vehicle size increased, however, the larger the stem size overridden increased, probably because

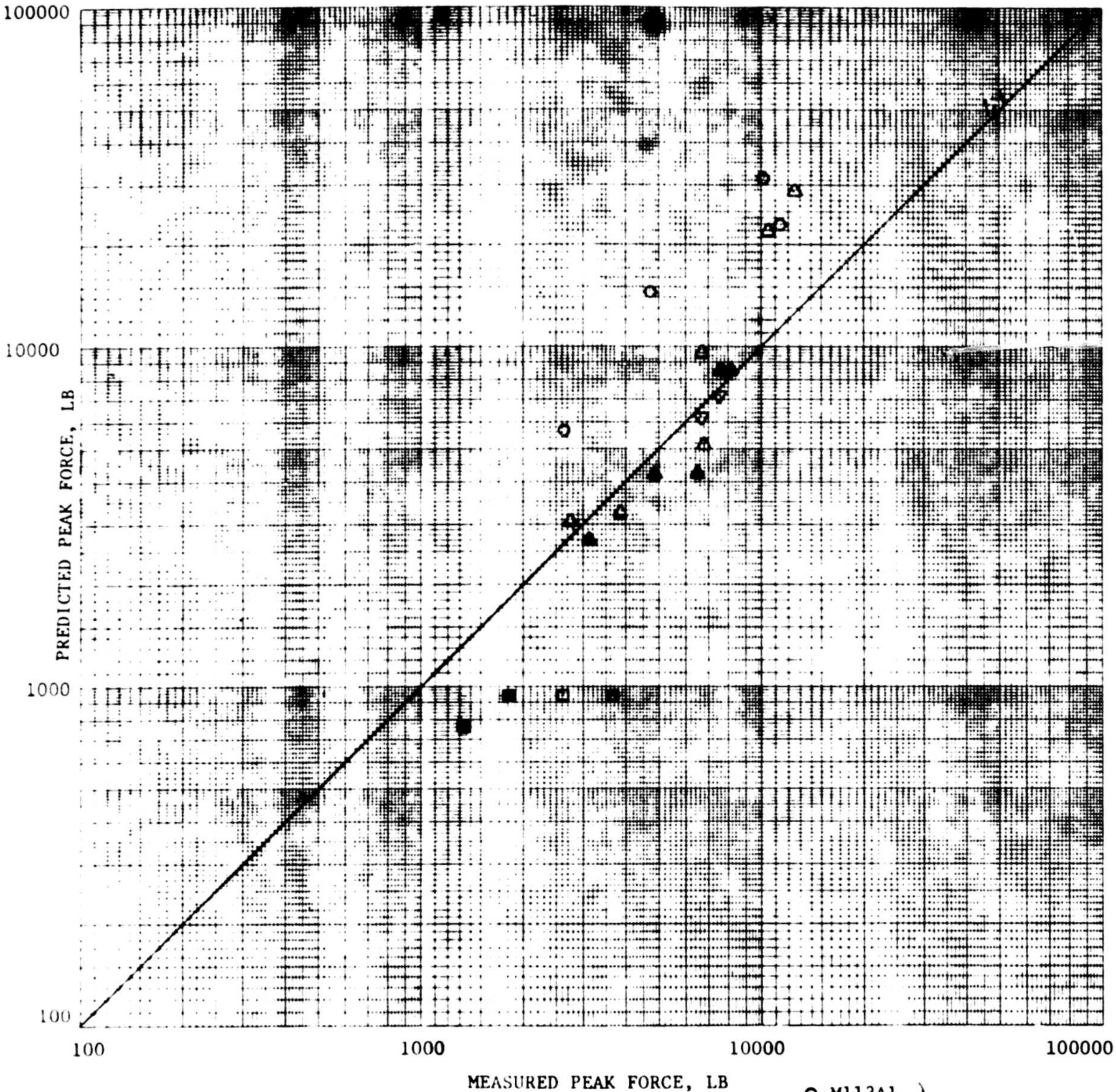


Figure 3. **Eglin-Houghton single-tree override tests**

○ M113A1
△ M35A2 } Eglin
□ M151
▽ M35A2 (Houghton)
Oaks (open symbol)
Pines (closed symbol)

of the increased feeling of security experienced by the driver with the larger vehicles. However, the driver apparently felt that on most occasions it was faster to maneuver around than to override larger trees. The important result derived from the tree-override tests was that the assumption made in AMC-71 that the driver will override up to the maximum diameter negotiable, then maneuver, is invalid in cross-country operation. Further testing is in order, therefore, to allow correct modeling of vehicle-driver interreaction in forested terrain.

Observation in forested terrain

An important aspect not considered in AMC-71 was observed during the conduct of tests at some of the forested sites where trees were closely spaced. In both single- and multiple-tree-override tests in forested terrains, one of the main factors in determining measured vehicle speed where override was necessary was the influence of surrounding vegetation on the falling tree or trees. Frequently, in those terrains where tree spacing was close, trees being overridden fell into the surrounding trees and lodged off the ground making it much more difficult for the vehicle to override; in such cases the vehicle would usually continue up onto the trees until override was completed or the traction elements no longer contacted the ground surface. Accordingly, sufficient vegetation testing should be conducted to produce a data base for development of relations that will model interference from other trees in cross-country operation in forested terrains.

Maneuvering Submodel

Though used as a coupling routine in AMC-71, the maneuvering submodel is closely associated with parts of the obstacle and vegetation submodels. The maneuvering submodel itself considers only two variables (mean obstacle spacing and area denied) and merely adjusts the minimum of the speeds from soil, slope, ride dynamics, and visibility to account for vehicle maneuvering required to avoid vegetation or obstacles too large for the vehicle to override. Based on the predicted and measured

speed results for terrain-unit tests where maneuvering limited predicted speed, the maneuvering submodel needs to be improved. Relative deviations for wheeled vehicles in maneuver areas were 114 percent, whereas those for tracked vehicles were somewhat lower at 44 percent. The results of validation tests in maneuver areas, which show the average relative deviation to be 88.8 percent, indicate that the maneuvering submodel is not accurate and that further testing should be conducted to revise this important cross-country mobility factor. More consideration should be given to the actual override being completed rather than the possibilities for override, and the maneuvering equation should be revised to include various vehicle attributes that affect maneuverability.

Vehicle Ride Dynamics Module

The ride dynamics module computes speed at which a vehicle can traverse discrete obstacles or continuous surface roughness without exceeding specified limiting shock or vibration criteria. The surface roughness relation consists of speed values corresponding to the limit of driver tolerance to random vibrations, as a function of root-mean-square (rms) terrain profile elevation. This limiting condition is defined in terms of the rate at which power can reasonably be absorbed by the human body. The present criterion used in the dynamics module for driver tolerance limit is 6 watts of absorbed power. However, it became evident during this program that drivers were generally willing to maintain speeds that produced absorbed power levels in excess of 6 watts (more in the neighborhood of about 9 watts).

The obstacle impact relation is a function of obstacle height - speed at which a vertical acceleration of 2.5 g's is experienced at the driver's station when the vehicle encounters discrete obstacles. This relation is used with the obstacle submodel. The simulation of vehicle dynamics is necessarily complex, requiring detailed vehicle data. In the interest of expediency, AMC-71 was initally programmed for the five

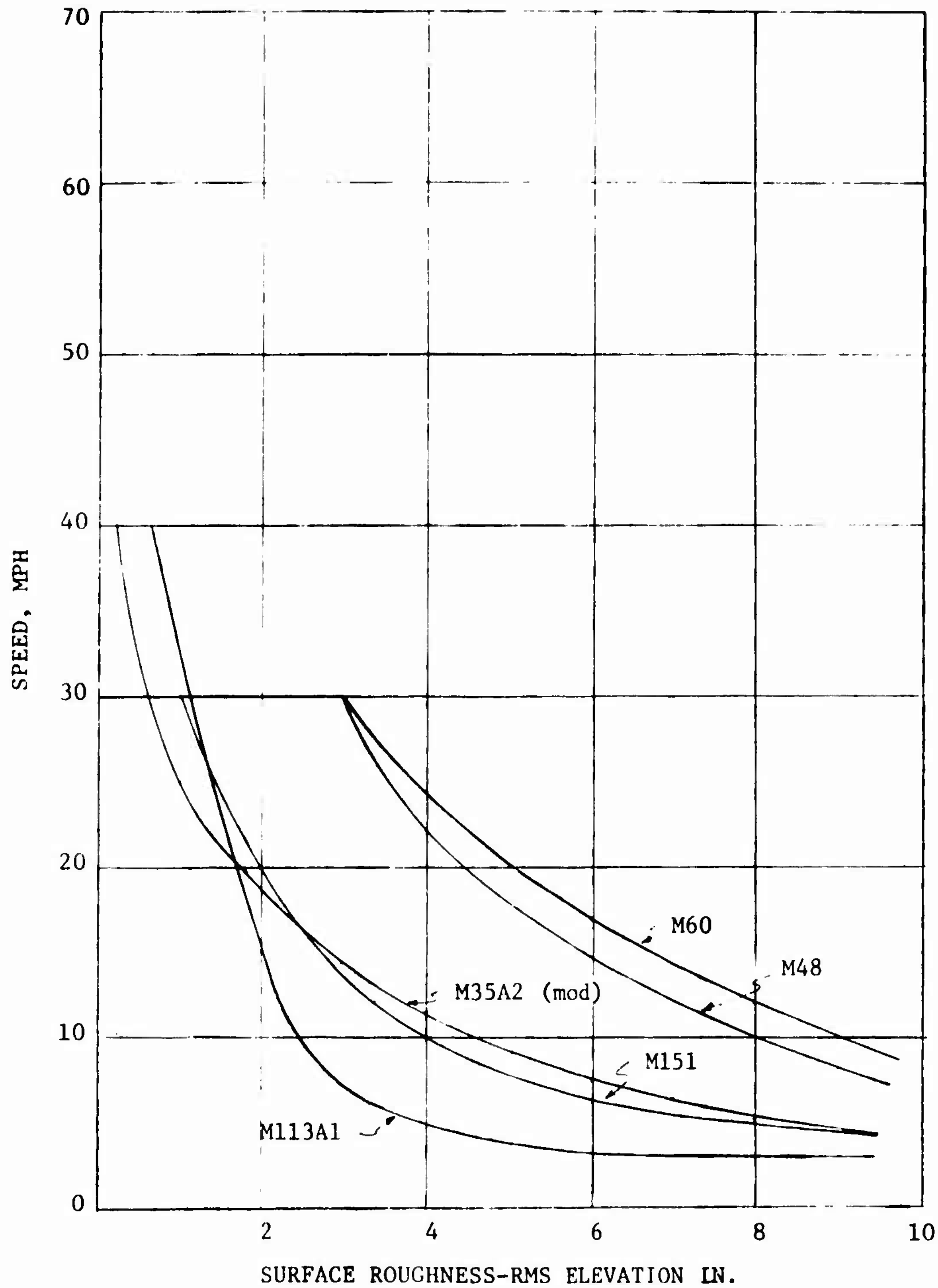


Figure 4. Speed vs surface roughness computer-simulated data

Table 3

Summary Evaluation of Vehicle Speed Data, Terrain-Unit Tests

Factor Controlling Speed*	Number of Tests	Vehicle	Range of Deviation mph	Mean Algebraic Deviation mph	Mean Absolute Deviation mph	Relative Deviation %	Root Mean Square Deviation mph
5	61	M151	-15.5 to +16.1	4.4	5.9	51.9	7.2
	52	M35A2	- 3.7 to +19.3	6.8	6.8	46.0	7.9
	41	M113A1	-10.9 to +14.1	-1.5	4.8	29.6	6.2
6	4	M151	- 1.4 to + 7.3	1.8	2.8	18.2	3.9
	13	M35A2	- 3.2 to + 7.2	0.1	2.4	25.0	3.0
	23	M113A1	- 4.1 to + 6.9	1.5	2.4	13.7	2.8
	20	M48A3	- 3.7 to +17.0	2.6	4.0	23.0	6.5
	26	M60A1	-13.5 to + 4.4	-2.0	3.2	18.1	4.3
7	31	M151	- 3.1 to +21.2	3.9	5.5	37.9	7.7
	26	M35A2	- 2.4 to +19.8	4.1	4.4	32.4	6.2
	19	M113A1	- 4.9 to + 6.9	-0.6	2.7	14.3	3.2
	19	M48A3	- 5.8 to + 7.2	-0.4	2.5	13.4	3.1
	1	M60A1	-	-2.8	2.8	17.9	2.8
8	21	M151	- 1.7 to +20.4	9.2	9.4	118.8	10.7
	16	M35A2	- 4.4 to +11.4	5.5	6.8	107.9	7.4
	17	M113A1	- 9.8 to + 8.8	0.6	4.3	41.3	5.2
	4	M48A3	+ 0.7 to + 5.5	3.6	3.6	56.2	4.0
9	3	M151	- 3.5 to + 1.6	-0.2	2.2	12.7	2.4
	22**	M35A2	- 5.9 to +13.2	7.0	7.5	86.2	8.0
	31**	M113A1	- 3.5 to +12.4	4.9	5.4	49.1	6.5
	9	M48A3	- 0.7 to +12.7	3.0	3.2	36.8	4.8
	8	M60A1	- 8.6 to + 3.5	-0.4	3.3	22.3	4.1
10	15	M151	- 9.5 to + 7.6	-1.7	4.7	50.0	5.5
	3	M35A2	- 3.2 to - 0.7	-1.6	1.6	20.0	2.0
	3	M113A1	- 7.5 to - 3.5	-5.5	5.5	50.0	5.7

* See paragraph 10b.

** One test resulted in immobilization due to factor 9.

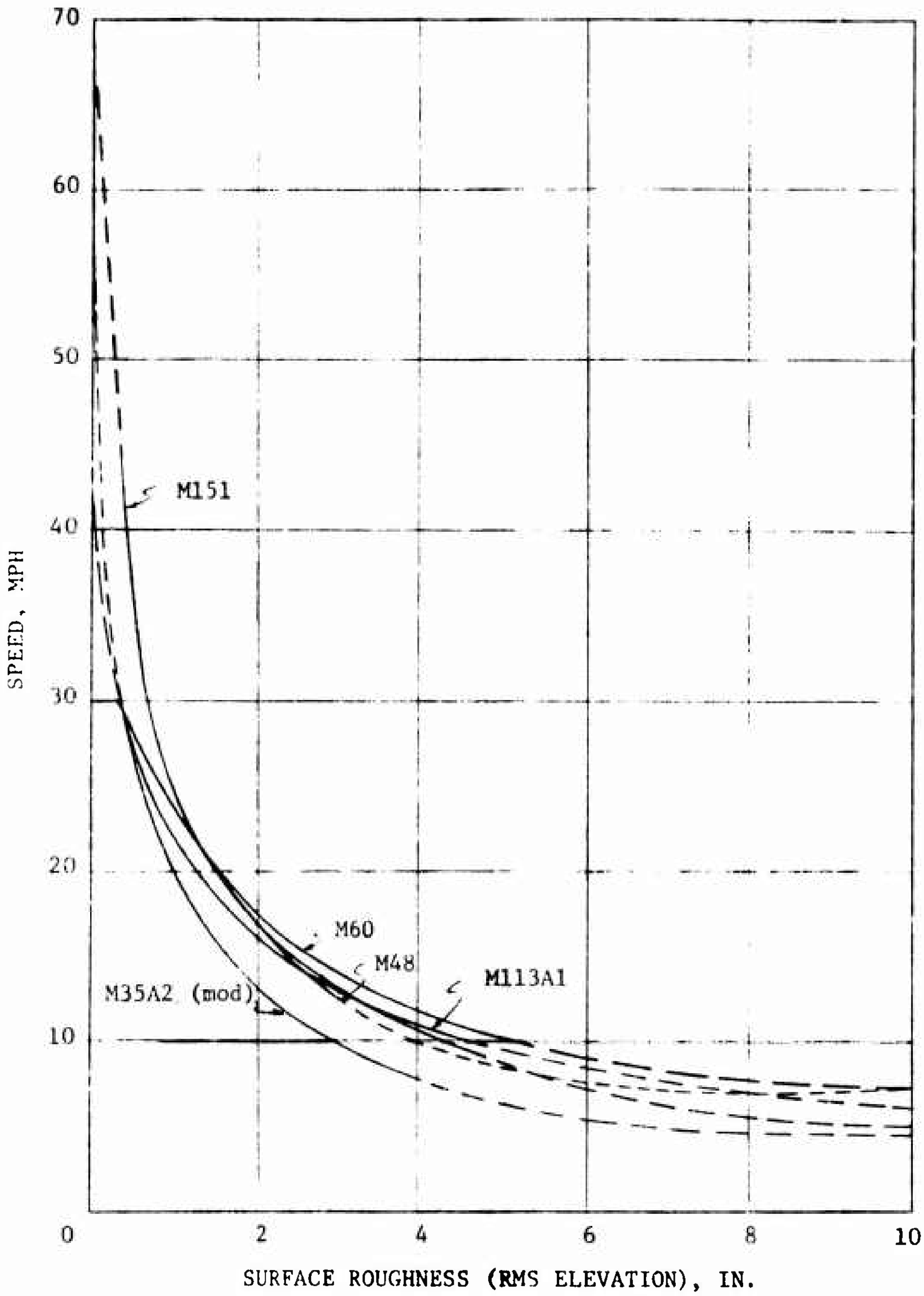


Figure 5. Speed vs surface roughness, field-measured data

validation vehicles only, rather than for tracked and wheeled vehicles of general configuration. (Since the completion of AMC-71, however, generalized digital computer models have been established.) In accordance with the scope of this study, the ride relations determined from the initial ride dynamics simulation were used in the primary comparisons between predicted and measured speeds.

<u>Predictions based on simulated relations</u>

The computer-simulated ride relations for surface roughness (rms elevation versus speed) shown in Figure 4 were used in AMC-71 to predict speeds for all validation tests.

Results of terrain-unit tests in which surface roughness (factor 5) controlled predicted vehicle speed are shown in Table 3. The relative deviations for the vehicles are somewhat greater than the acceptable limit (20 percent), indicating improvement is needed.

<u>Predictions based on measured relations</u>

An rms elevation versus speed curve (Figure 5) was developed for each vehicle based on the measured speed results in 32 terrain units. These are tests in which field observations during the test and driver and navigator comments indicated that measured vehicle speed was probably limited by surface roughness.

The relations based on field-measured data were put into the vehicle characteristics file in place of the simulated relations, and new speed predictions were made for all validation tests using AMC-71. The new results for tests wherein surface roughness controlled predicted vehicle speed are shown in the following tabulation:

No. of Tests	Vehicle	Range of Deviation mph	Mean Algebraic Deviation mph	Mean Absolute Deviation mph	Relative Deviation %	Root Mean Square Deviation mph
		Numerical Evaluation Parameters				
64	M151	-11.6 to 15.1	2.2	4.4	25.0	5.6
66	M35A2	- 6.1 to 15.3	1.6	3.0	20.1	4.2
42	M113A1	- 6.2 to 5.1	-0.8	2.1	11.7	2.6
9	M48	- 5.3 to 13.1	1.4	3.8	20.2	5.2
3	M60	- 1.3 to 1.1	-0.3	1.1	7.0	1.1

The above results, when compared with the simulated results, show marked improvement in AMC-71 prediction accuracy when measured speed versus rms elevation relations are used. The data show that the relative deviation for each vehicle is near or below the 20 percent limit, indicating acceptable prediction accuracy.

Single-Terrain-Unit Speed Tests

Results from terrain-unit speed tests in this study were analyzed for traverse terrain units longer than about 400 ft and for single terrain units outside the traverses. Results of the terrain-unit tests were analyzed according to the factors that controlled the predicted speed in each unit for each vehicle.

The results in Table 3 indicate that the factor that controlled speed in most terrain units was surface roughness. The relative deviations for the vehicles were somewhat greater than the acceptable limit (20 percent), indicating improvement is needed in surface roughness modeling. Surface roughness governed the predicted speed most often for the wheeled vehicles--the M151 and M35A2. The tracked vehicle speeds were influenced more by visibility (factor 7), maneuvering (factor 8), and combinations of all resisting forces (factor 9). The data indicate

relatively good modeling for all vehicles in terrains in which predicted vehicle speeds were limited by combined surface and slope resistances (factor 6). For factor 6, relative deviations for the M151, M113A1, and M60 were less than the 20 percent deviation limit considered acceptable in this analysis. Results for the tracked vehicles were also acceptable for those terrains in which visibility in the terrain unit (factor 7) limited the predicted speeds. However, relative deviations for the wheeled vehicles in these units exceeded 32 percent.

The most glaring deficiency in the model is in the vegetation submodel. Predicted speeds generally were 1.5 to 2 times faster than measured speeds, especially in those terrain units in which maneuvering dictated the predicted vehicle speed. Maneuvering (factor 8) produced relative deviations greater than 20 percent for all vehicles and as high as 118.8 percent for the M151. Consequently, assumptions and techniques used in formulation of this submodel appear to need revision. The combination of all resisting forces (factor 9), which is directly related to the vegetation submodel, produced relative deviations greater than 20 percent for all vehicles except the M35A2.

Analysis of Results of Traverse Tests

Two categories of terrain data were used in analyzing the results of the traverse tests: (a) specific, i.e. values measured at each test site, and (b) classed, i.e. values assembled into terrain factor classes on each traverse. Vehicle performances were predicted with AMC-71 using each category; the predicted performances were then compared with performances measured in the field. Predictions using the terrain values collected in this study should represent the best predictions possible, since all the data were actually measured, not estimated or interpreted from air photos or other sources.

Speed tests on traverses,
specific terrain values

Predicted traverse speeds are plotted versus measured traverse speeds for each vehicle at each test site in Figure 6. The plotted data shows that measured vehicle speeds ranged from 4.1 mph for the M35A2 to 25.2 mph for the M151. Predicted vehicle speeds ranged from 5.2 mph for M113A1 to 29 mph for the M151. Analyses of these tests indicate the following:

		Numerical Evaluation Parameters				
No. of Tests	Vehicle	Range of Speed Deviation mph	Mean Algebraic Speed Deviation mph	Mean Absolute Speed Deviation mph	Relative Deviation %	Root Mean Square Deviation mph
17	M151	-0.6 to 12.6	4.3	4.3	33.6	6.0
16	M35A2	0.5 to 0.4	5.2	5.2	47.7	5.7
17	M113A1	-5.1 to 7.7	0.7	2.9	21.0	3.7
7	M48	0.5 to 4.4	2.0	2.0	14.8	2.3
4	M60	-5.0 to 0.2	-1.6	1.8	10.3	2.6

The overall weighted average relative deviation for all five vehicles was 30.1 percent, or 10 percent greater than the maximum relative deviation of 20 percent considered acceptable for prediction accuracy with AMC-71. Results indicate that in general, predicted speeds were higher than measured speeds by +2.9 mph overall. Large deviations in predicted and measured results occurred in traverse tests at all the test locations where forested terrain was encountered, with the largest occurring at EAFB. Speeds predicted from the vegetation submodel are generally higher than those actually obtained in field tests. All traverses at EAFB were composed of terrain units with significant-to-dense vegetation; if the EAFB tests were deleted from the analysis, the average relative deviation would be reduced to 21 percent, or only

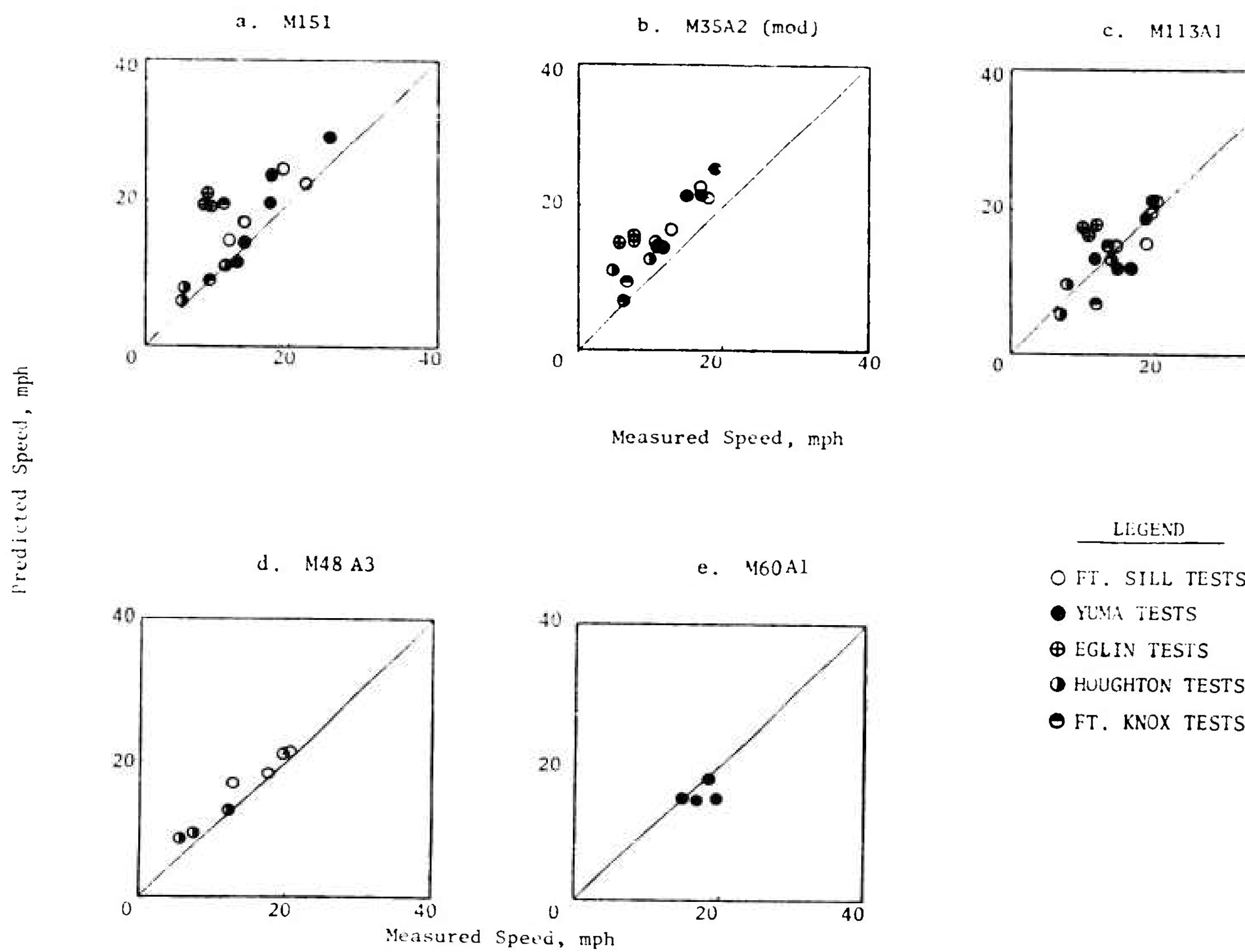


Figure 6. Comparison of measured and predicted speeds for validation vehicles on traverse values

1 percent greater than the acceptable prediction accuracy. Furthermore, it has been shown that one of the present weaknesses of AMC-71 appears to be the modeling of vehicle performance in forested terrain where maneuvering and vehicle override are significant factors. Therefore, modeling of vegetation and maneuvering appears to be one of the major revisions necessary for improved prediction accuracy with AMC-71 for traverse and terrain-unit operation.

The overall relative deviation for the M151 was 33.6 percent although relative deviations were within acceptable limits (20 percent) for traverse tests at FS, YPG, and HTN. At the same time, the greatest overall relative deviation was obtained for the M35A2 (47.7 percent) with deviations for tests at all five locations greater than the 20 percent acceptable limit. In the field tests the M35A2 was slow to accelerate, and unless the unit was of sufficient length to allow the vehicle to overcome its slow acceleration characteristics, it failed to achieve a maximum speed representative of the terrain conditions. At present AMC-71 does not account for vehicle acceleration-deceleration at the edge of terrain units as a vehicle moves from one unit to the next. Therefore, a contributing factor to the large deviations in all traverses for the M35A2 was probably the lack of an acceleration-deceleration routine in the model.

Further analysis of traverse speeds show that the weighted relative deviation for all five vehicles using the measured surface roughness relations for predictions was 27.7 percent, which is slightly less than the 30.1 percent deviation obtained with the simulated relations. However, if the EAFB data were deleted from the average, the weighted relative deviation would be reduced to a respectable 15 percent. Stated more simply, this analysis indicates that if simulated ride dynamics relations were corrected or measured relations were used and the maneuvering relations corrected, AMC-71 would, in fact, have an overall prediction accuracy of at least 85 percent for the traverse conditions.

Predicted and measured traverse speeds for each vehicle were based on classed terrain data at each site. The overall weighted average

relative deviation for all five vehicles was 31.1 percent, or 1.0 percent higher than the weighted deviation obtained for the specified terrain values. Better prediction accuracy was attained for the traverse tests than for the terrain-unit tests. The reason for the better accuracy of the traverse predictions is primarily the averaging of the terrain-unit speeds that takes place in computing traverse speed.

Summary

Analysis of relations involved in the submodel and single terrain unit tests indicate that although some refinement can be made, in general, the power train, measured surface roughness, soil traction, slope, visibility, obstacle spacing, area denied and single tree override relations have an acceptable prediction accuracy. The data also show that marked improvement is needed in the simulated surface roughness, obstacle override, and especially in the maneuver and vegetation relations. Consideration should be given to include relations for tree override when interference occurs, acceleration-deceleration at terrain unit boundaries, and override of deformable obstacles.

Analysis of the traverse tests data showed an overall relative deviation of 30.1 percent or a prediction accuracy of 69.9 percent. Results of the traverse tests indicate that on the average, predicted speeds were higher than measured speeds by +2.9 mph overall. Therefore, study and revision are needed in some areas of the AMC-71 mobility model to improve prediction accuracy. Further analysis show that if the simulated surface roughness relations used throughout this study were corrected or are replaced by measured relations and the maneuver relations were corrected, AMC-71 would have an overall speed prediction accuracy of at least 85 percent for the traverse conditions tested.

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APPENDIX A: DEFINITIONS OF VEHICLE, SOIL, AND MATHEMATICAL TERMS

Vehicle terms used in this report are as follows:

a. Absorbed power. The rate at which vibrational energy is absorbed by a vehicle occupant. It is a measure of ride quality.

b. Immobilization. The inability of a self-propelled vehicle to go forward.

c. Optimum drawbar pull. A point on the drawbar pull versus slip curve at which work output of the track or wheel is the most efficient.

d. Pass. One trip of a vehicle over a test course.

e. Ride. The quality of vibratory motions caused by random terrain irregularities as sensed by a vehicle occupant.

f. Slip. The percentage of track or wheel movement ineffective in thrusting a vehicle forward.

g. Motion resistance (MR/W). The amount of force required to tow a test vehicle in neutral gear under given test conditions, expressed as a percentage of the vehicle test weight.

h. Vehicle cone index for one pass (VCI). The minimum rating cone index (RCI) that will permit a vehicle to complete one pass.

Soil terms used are as follows:

a. Coarse-grained soil. A soil of which more than 50 percent of the grains, by weight, will be retained on a No. 200 sieve (larger than 0.074 mm in diameter).

b. Fine-grained soil. A soil of which more than 50 percent of the grains, by weight, will pass through a No. 200 U. S. standard sieve (smaller than 0.074 mm in diameter).

c. Unified Soil Classification System (USCS). A soil classification system based on identification of soils according to their textural and plasticity qualities and on their grouping with respect to their engineering behavior.

d. Cone index (CI). An index of shearing resistance of soil obtained with the cone penetrometer. The value, considered dimensionless, represents the resistance of the soil to penetration of a 30-deg cone of 0.5-in.^{2} base or projected area at a penetration rate of 6 ft/min.

e. Rating cone index (RCI). Produce of CI and remolding index (RI). RI is the ratio of remolding soil strength to original strength. RCI expresses the soil strength rating of a soil subjected to vehicular traffic.

Mathematical terms used in this report are as follows:

a. Deviation. Predicted value (P) minus the measured value (M), P - M.

b. Mean absolute deviation. The average of the numerical differences between measured and predicted values.

c. Mean algebraic deviation. The average of the algebraic differences between measured and predicted values.

d. Range of deviation. The algebraic extremes in the deviations between measured and predicted values.

e. Relative deviation. The absolute deviations of a measured value from a predicted value expressed as a percentage of the measured value, i.e.

$$\text{Relative deviation, } \% = \sum \frac{P - M}{M}$$

f. Root mean square deviation. The square root of the average of the squares of the deviations are measured from predicted values expressed by the following equation:

$$\sqrt{\frac{\sum (\text{Deviations})^2}{\text{Number of deviations}}}$$

In accordance with ER 70-2-3, paragraph 6c(1)(b), dated 15 February 1973, a facsimile catalog card in Library of Congress format is reproduced below.

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